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INDUSTRIAL TURBIDIMETERS WITH AUTOMATIC CLEANING OF MEASURING CELLS

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Abstract – The main problem in operation of industrial turbidimeters is buildup of parasitic deposits on transparent windows of light sources and photodetectors. Two different ways of solving the problem of noise-immune measurements of turbidity are discussed. The first way consists in realization of so called turbidimeters with variable gauge length. Another way lays in the field of use of photosensor arrays and image processing. In both cases presence of an automatic cleaning system is necessary.

Keywords: turbidimeter, cleaning system, photosensor array

1. INTRODUCTION

1.1. Turbidity and turbidimeters

Measurements of turbidity are very important for water quality control and quality control of other liquids in various manufacturing processes and for environmental monitoring.

Turbidity is the optical property of a liquid that causes light to be scattered and absorbed rather than transmitted in line direction. The cause of the light scattering is the presence of small particles having optical properties different from ones for the liquid medium [1]. So we can measure particles content by measuring of scattered or attenuated radiation. Actually mass concentration of particles is the output in most of industrial turbidimeters along with or instead of turbidity.

Turbidimeters based on measuring of scattered radiation are known as nephelometers. As a rule a nephelometer's photodetector has to be situated at an angle of 90º or another angle with respect to direction of radiation. Turbidimeters based on measuring of attenuated radiation has a light source and a photoreceiver whose optical axes are on the same line. They are termed as "transmission" turbidimeters [2].

Industrial turbidimeters differ markedly from laboratory ones in their constructions, schemes and algorithms. Industrial turbidimeters have to possess not only sufficient accuracy but metrological reliability in the first place. The main problem in operation of industrial turbidimeters is the soiling or dirtying of transparent windows of light sources and photodetectors that sometimes makes measurements difficult or even impossible. If the function of a turbidimeter is to work in suspensions or in liquids containing solid matter particles only, this problem may be solved by application of mechanical wipers, ultrasound vibrators, pneumatic or hydraulic washers. In case the controlled medium contains adhesive particles (oil, gum) the mentioned means become fruitless: it is hard to obtain the full clearance. For such media special combined solutions must be applied, for example, compensation of windows dirtying using ratiometric principle [3] and adaptive or periodical cleaning.

1.2. Ratiometric principle

Suppose a measuring device includes a light source and a photodetector dynamically positioned one towards another. Such type of turbidimeters is based on the following relationships:

$$U_1 = k \cdot A_0 \cdot e^{-L_1 EC}, \quad (1)$$

$$U_2 = k \cdot A_0 \cdot e^{-L_2 EC}, \quad (2)$$

where U_1, U_2 - output signals of the photodetector corresponding to L_1, L_2 - distances between the source and the photodetector ($L_2>L_1$); A_0 - intensity of transmitted light; k - coefficient of transduction depending on transparency of windows and conversion transconductance of the photodetector (in fact, it is the coefficient of windows transparency); E - specific extinction coefficient; C - concentration of particles.

We can get from (1) and (2) the following expressions for C and k:

$$C = \frac{\ln\left(\frac{U_1}{U_2}\right)}{E(L_2 - L_1)}, \quad (3)$$

$$k = \frac{U_2}{A_0} \cdot \left(\frac{U_1}{U_2}\right)^{\frac{L_2}{L_2 - L_1}}. \quad (4)$$

We can see in (3) that unstable coefficients k and A_0 are abridged, and multipliers of denominator (L_2-L_1) and E are conditionally constant. So it is not required to provide high stability of light source and transduction channel (including optical path). And according to (4) we can determine k and compare the current value k with a critical limit k_{min}. If $k < k_{min}$ a procedure of windows cleaning has to be initiated.

Alternative method of windows dirtying compensation is so called Four-beam pulsed light method [4, 5]. The method consists in the following. There are two light sources and two photoreceivers located so that each source is directed to a photoreceiver and its radiation scattered under 90° is directed to another photoreceiver. The sources are pulsed consequtively. Two signals are detected at each of the photoreceivers. Then these four signals are used for calculating the special ratio which is free of unstable parameters and depends on concentration only. And it is of no small importance that all four coefficients depending on degrees of dirtying of four windows, are abridged in the ratio. So nonidentity of windows dirtying doesn't affect the result.

1.3. Methods of windows cleaning

Various ways and constructions of cleaning systems can be used in sensors of turbidimeters: wiper with electromotor drive [6, 7]; rubber brushes with pneumatic drive [8]; ultrasound oscillations of probe housing [9] and so on. As a rule, wipers are not necessary in devices that realize Four-beam pulsed light method, but preventive maintenance should include periodical rinsing with hot water or solvent. In all cases the problem of effective operation of cleaning system takes place. As a rule, frequent periodical switching of cleaning system is not reasonable and more acceptable is to switch it when the degree of dirtying really goes above the determined limit.

2. TURBIDIMETER WITH VARIABLE GAUGE LENGTH AND AUTOMATIC CLEANING SYSTEM

Our proposals concerning improvement of traditional turbidimeters in terms of obtaining reliable and noise-immune operation in conditions of adhesive dispersed particles and windows' transparency decreasing are summarized in the following:

1) Ratiometric principle may be easy realized by means of transmission turbidimeters with variable gauge length (distance between a light source and a photodetector) [10]. In spite of obvious difficulties consisting in the presence of moving parts in such devices they have some features that can be useful in many cases:
   - full identity of windows dirtying for measuring U_1 and U_2 according to (1), (2) is natural because measurements are executed with the same pair of source and photodetector;
   - possibility to adapt gauge length according to current concentration for improvement of its metrological properties;
   - it is possible to determine current degree of dirtying of the light source and photodetectors' windows; this information may be used, for example, for opportune switching of a special cleaning device.
2) It is necessary to have combination of chemical and mechanical (or ultrasound) influences upon dirtying or soiling layer.
3) For cleaning efficiency and minimizing detergent expenditure it is worthwhile to isolate a measuring cell of a turbidimeter during time of cleaning.

One of possible constructions of a ratiometric transmission single-beam turbidimeters provided with automatic cleaning system is shown in Fig. 1.

Its construction includes: measuring cell 1 filled by liquid medium 2; photodetector 3; light source 4; drive 5; guide element 6; moving element 7; transparent window 8; displacement sensor 9; sylphon 10; controller 11; ultrasound vibrator 12; controlled screens 13; screens' drive 14; liquid detergent feed hose 15; liquid detergent vessel 16; controlled plunger 17; plunger drive 18.

Variation of distance between the photodetector 3 and the window 8 is carried out by means of the drive 5, the guide element 6 and the moving element 7. The sylphon 10 serves as a delimiter for liquid and air mediums and provides the leakproofness of the construction. Functioning of the turbidimeter is supported by the controller 11 which has analog inputs for the photodetector's and the displacement sensor's signals and control outputs: for the source and the ultrasound vibrator switching and for the commutation and reversion of the drives 5, 14, 18. Gauge length in the described device is the distance between the window of photodetector 3 and the moving window 8.

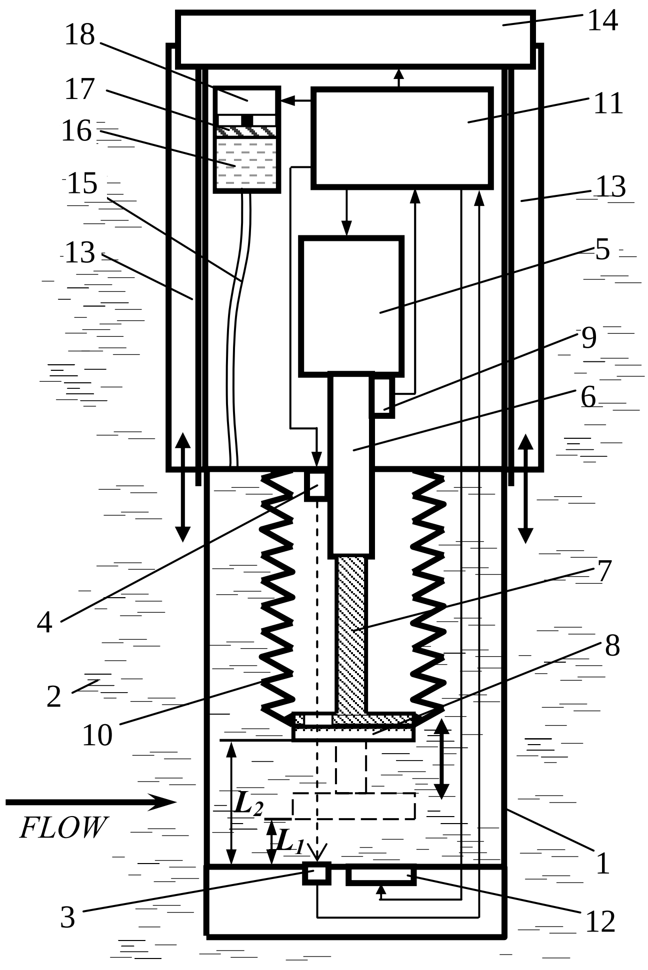


Fig. 1. Example of a ratiometric transmission single-beam turbidimeter provided with automatic cleaning system

The turbidimeter operation comes to generation of software-controlled signals on the controller's outputs for all drives, the light source and the ultrasound vibrator, measurement of the photodetector and the displacement sensor output signals in corresponding time and calculations of concentration *C* and coefficient *k* according to (3) and (4).

If $k < k_{min}$ a procedure of windows cleaning starts. It includes closing the measuring cell 1 by special controlled screens 13, pressing-out the liquid detergent from the vessel 16 and switching the ultrasound vibrator 12. Ultrasound action is kept on a few minutes. During this time very effective cleaning of the measuring cell takes place including cleaning of the transparent window 8 and the window of the photodetector 3 under the combined influence of ultrasound and chemical reaction between the detergent and dirtying deposits inside a small volume of the measuring cell. After cleaning procedure the screens 13 are withdrawn to the initial position and the liquid flow washes away remains of dirt.

3. APPLICATION OF PHOTOSENSOR ARRAYS AS A WAY OF NOISE-IMMUNE MEASUREMENT OF TURBIDITY

3.1. General idea of photosensor arrays application

Another way of noise-immune measurement of turbidity and automatic determination of degree of windows dirtying for opportune switching of a cleaning device is application of 2D photosensor arrays.

Our idea consists in the following. We use a 2D photosensor array instead of a single photodetector. A lens positioned between the glass window and the photosensor array realizes projection of the image derived on the outside of the window onto the photosensor array. If we have a transmission turbidimeter then a ray from the light source produces a bright spot on the surface of the photodetector window. The brightness of this spot depends on intensity of the light source, transparency of the light source window and turbidity of the liquid medium. Diffusiveness of this spot depends on turbidity only. And besides this spot the image contents randomly distributed spots of parasitic deposits: bubbles of air, stains of black oil, insoluble deposits of salts and so on. Fig. 2 illustrates various types of such deposits.

Of course, presence of such deposits distorts results of turbidity measurements. However, up to certain limits deposits effect may be reduced to zero by exclusively algorithmic methods such as noise filtering. But if deposits' area exceeds 20..25 % of total photosensor array area it would be reasonable to switch on a cleaning system because distortions of the light spot image produced by averaging effect of filtering would be unacceptable (resulting error may be of the order of 5 % in that case).

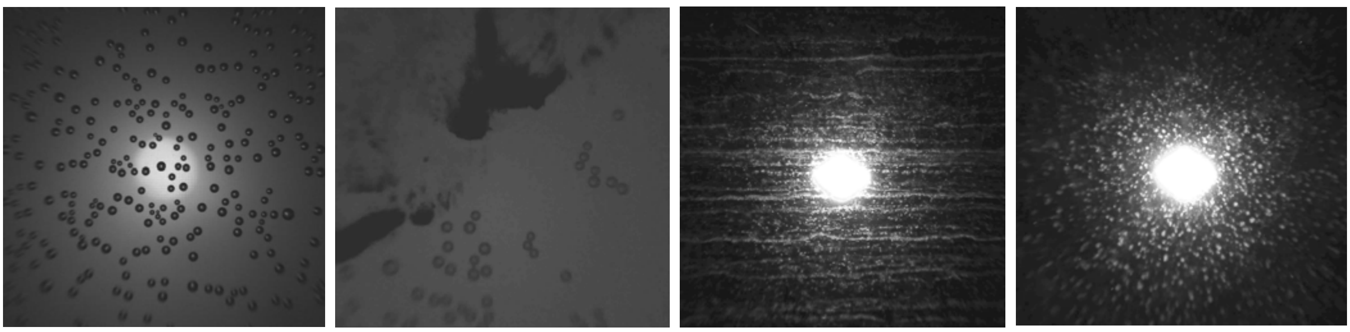
Thus information about relative area of deposits may be a basis for cleaning system functioning rationalization in the sense of opportune switching of such a system.

Furthermore, up-to-date technologies of pattern recognition make it possible to determine not only amount of deposits but also their type. Such information would help to choose adequate method of cleaning.

Every type of deposits has its specific graphical features. For example: air bubbles always have regular round shape and their images have bright glares inside (Fig. 2, a); stains of black oil have usually irregular shape and uniform dark flat coloration (Fig. 2, b); salt deposits often have laminated or featherlike structure (Fig. 2, c); colonies of algae produce a layer of small green dots on glass surface (Fig. 2, d).

Various methods known from pattern recognition theory may be proposed for detection of this or that type of deposits. For example, criterion of air bubbles detection is average roundness coefficient for deposit spots shown in Fig. 2, a, b. Relative area and coloration density of spots may be used as indicators for detection of black oil stains. And according to the determined type of deposit the cleaning system has to operate in adequate mode. For example, in case of presence of air bubbles only a single cycle of a wiper must be applied instead of complex procedure of chemical cleaning. In case of salt deposits wipers or ultrasound vibrators are effective. In case of gum or oil residue it is necessary to apply methods of chemical cleaning and full cycle of operation of cleaning cameras such as shown in Fig. 1.

Evident advantage of turbidimeters based on the proposed scheme in relation to the described above turbidimeters with variable gauge length consists in absence or minimal quantity of moving parts. This factor contributes to long service life of such turbidimeters.



a **b** **c** **d**

Fig. 2. Possible deposits on the surface of the photodetector's window:
air bubbles (a), stains of black oil with air bubbles (b), salt deposits (c), colony of green algae (d)

3.2. Photosensor array signal processing in detail

With help of special software it is possible to separate useful information from noise. Namely we must separate the image of the main spot from the image of parasitic deposits.

Analysis of brightness distribution for the image of the main spot helps to calculate invariant estimation of turbidity.

Such estimation may include calculating ratios of central pixels' brightness to brightness of pixels that are a certain distance away from the spot center. Note that the brightness of the pixels depends on the intensity of the light source and transparency of its window but the mentioned ratios do not.

Before consideration of turbidity determination method let's suppose that filtering is already applied and pictures of brightness distribution on a photosensor array are free of noise. Fig. 3 illustrates such pictures corresponding to 3 different values of turbidity. Also 3 corresponding plots for distribution of brightness along the horizontal median line of a frame are shown.

The simplest method of invariant determination of turbidity or concentration consists in the calculating ratios such as U_{0a} / U_{1a}, U_{0b} / U_{1b}, U_{0c} / U_{1c} which have to be substituted into a calibration formula (similar to (1)). Distance Δr between the spot center and the second estimating point has certain optimal values for different curves (different values of turbidity) in the sense of maximal accuracy of calculated results. But it is possible to find such value Δr that will be acceptable for all curves.

However, such simple method has the obvious disadvantage consisting in significant random errors of concentration determination through unstable form of curves such as sown in Fig. 3. These curves may have asymmetry and residual noise.

So for improving accuracy of concentration determination it is useful to perform statistical averaging of brightness values for the second estimating point. The averaging may be performed for pixels which are at a distance of Δr from the spot center in all directions (i.e. for pixels lying on circumference with a radius of Δr).

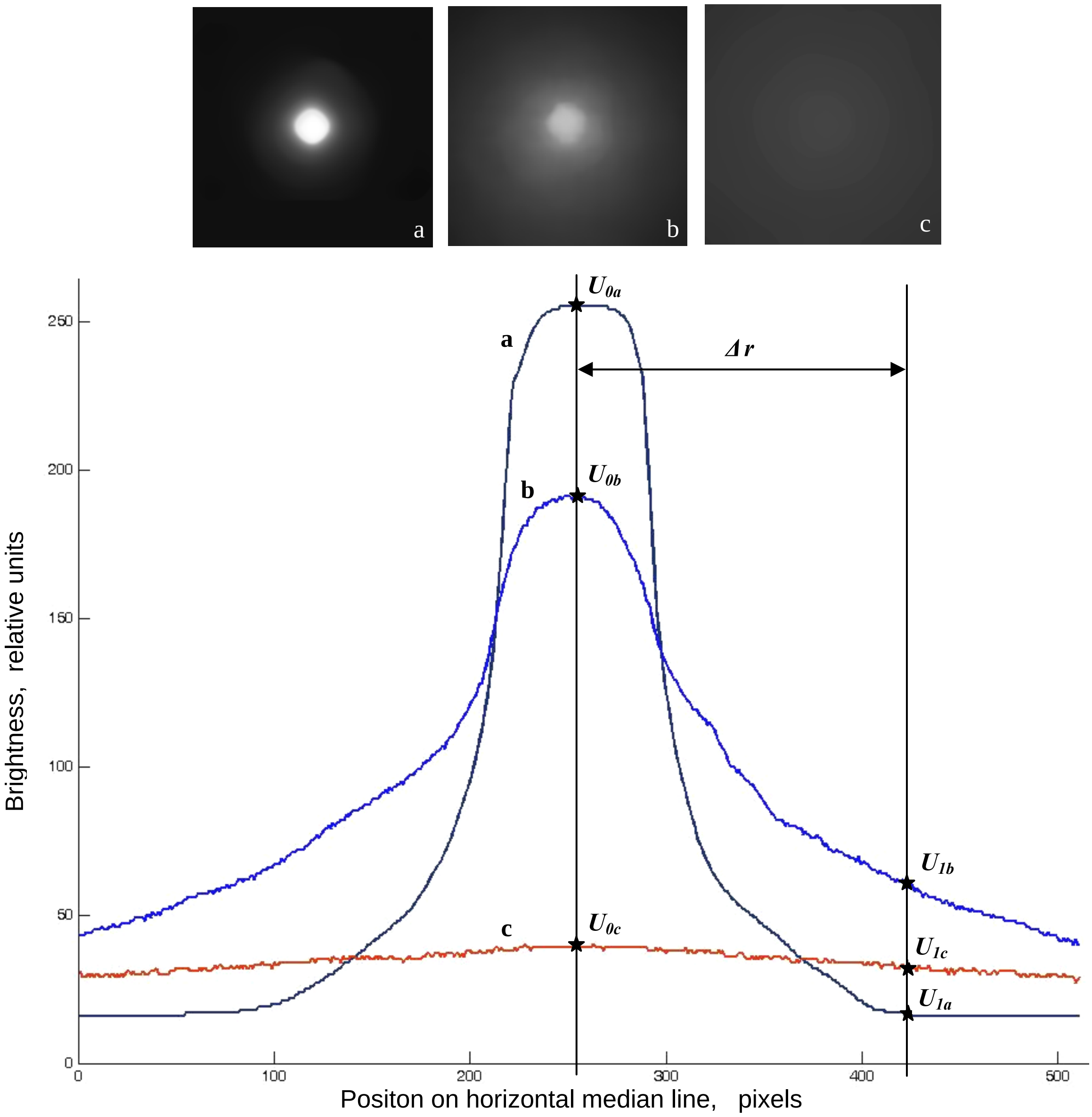


Fig. 3. Photosensor array images and corresponding distributions of brightness along the horizontal median line of a frame for different values of turbidity: a – 1 NTU; b – 100 NTU; c – 1000 NTU (NTU – special Nephelometric Turbidity Unit)

Now let's return to the question concerning parasitic deposits and consider some details of image processing.

An example of successive steps of image processing for separating the main spot image from the parasitic deposits image is shown in Fig. 4. The processing was realized by means of the Image Processing Toolbox from MATLAB 7. Pictures of Fig. 4 illustrate:

a – initial image of window's surface with bubbles of air:

b – transformed image after contrast-stretching transformation;

c – transformed image after median spatial filtering;

d – difference of images shown in Fig. 4, c and Fig. 4, b;

e – transformed image after application of the MATLAB function *edge*;

f – transformed image after successive applications of functions *imdilate, imfile, imclearborder, imerode* [11].

Required results of such transformations are 2 separated images: brightness distribution of the main spot (c) and black-and-white picture of parasitic deposits (f).

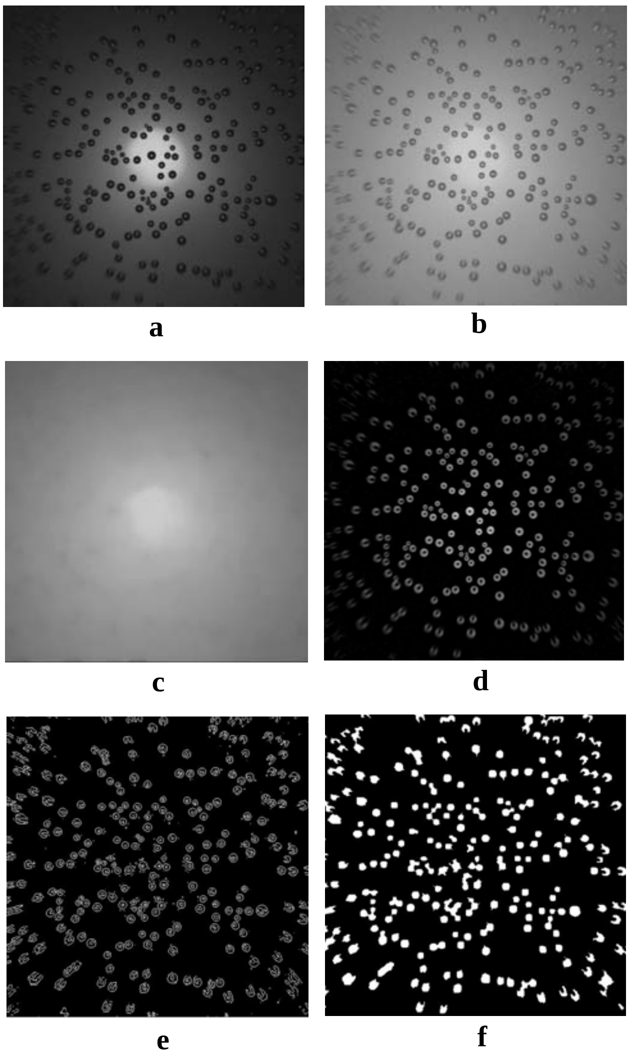


Fig. 4. Successive steps of image processing for the picture of air bubbles on the surface of the photodetector's window. Results of the processing are 2 separated images: brightness distribution of the main spot (c) and black-and-white picture of deposits (f)

The first is used for turbidity or concentration determination and the second is used for calculation of relative area S occupied by bubbles (white spots). If $S > S_{max}$ a procedure of windows cleaning has to be initiated. Here S_{max} is a certain critical value.

For the presented example such relative area makes up 8 % of the total area of the image. Note that for the shown picture of deposits, if a single traditional photodetector would be used, losses of the photodetector signal would be equal approximately the same 8 %. Our scheme and algorithms provide acquisition of useful signals almost without losses.

4. CONCLUSIONS

Different means for noise-immune measurements of turbidity are proposed. It is assumed that field turbidimeters of long-term durability must include automatic cleaning systems. According to conditions of application one of two design direction may be selected – turbidimeters with variable gauge length and turbidimeters with photosensor arrays. Due to rapid development of such electronic elements as photosensor arrays and corresponding processing controllers and achievements in the field of image processing the second direction seems to be more effective in most of cases.

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