Features of the signal registration and processing in the study of liquid flow medium by the refraction method

N M Grebenikova¹, R V Davydov¹ and V Yu Rud²

¹Higher School of applied physics and space technologies, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, 195251, Russia
²All Russian Research Institute of Phytopathology, Moscow Region 143050, Russia

E-mail: nadyagrebenikova@mail.ru

Abstract. Features of image formation and registration of the light-shadow boundary in flow refractometer are considered. A new design of refractometer was developed for the state control of poorly transparent and turbid flowing media containing big insoluble particles. A new algorithm for processing the image recorded on a photodiode array for determining of liquid flow parameters has been developed. A new method for contrast degree determining of the light-shadow border has been proposed taking into account features of registration and processing of optical signals. Experimental results are presented.

1. Introduction

Nowadays for flowing liquid state control are developed the different methods and devices [1-6]. During the measurements, the users give the greatest preference of non-contact methods: optical, ultrasonic and nuclear magnetic [1-3, 6-13]. That is due to the fact that contact of measuring instruments with the test liquid is almost impossible. This allows not to make changes in the flow structure, maintain the medium sterility, etc. The optical methods are the most widely used among them for various reasons [6-10, 14-18]. The measurements based on the use of the refraction phenomenon are considered to be the most universal among optical methods [14, 16-20]. The refractometer method has the great advantages in comparison with others – it can be used for liquid control both in stationary and flowing state. This increases greatly the functional possibility of refractometers. These devices can be used, for example. To control the degree of waste water, treatment, at various stages in the food, chemical and pharmaceutical industry. It showed be noted that the refraction method unlike other methods, except NMR [4, 21-24], does not change the physical structure, chemical composition and taste properties of the controlled liquid. Therefore, the development of new measurement methods and signal processing algorithms from detected laser radiation to improve the accuracy of determining the parameters of the liquid environment is an important task.

Besides, the researches showed that in some cases it is rather difficult to realize the control of liquid state by measuring the refractive index n. There are also a number of problems, which depend on the degree of liquid transparency, on its composition and the presence in it insoluble components of different sizes [16, 19, 20, 25-28]. One of the possible solutions of these problems in presented in our paper.

2. Refractometer design and reflection laser image processing algorithm

When working with liquid medium the cases often take place when flowing liquid media contain large insoluble compounds (for example, juice with pulp, medical suspensions, biological solutions, etc.) [3,
In these cases, it is slight incorrect to use the concept of refractive index \( n_m \) for such a medium. As at different moments of time in one and the same point of liquid medium, for example in pipeline, the liquid density will be different, as well as the composition of molecules and particles in medium. Scattering and multiple reflection of laser radiation used for measurement will take place on these molecules and particles. These factors do not allow to use the classical refractometer schemes to control the state of such liquid media, since it is very difficult to calibrate the instrument due to the large uncertainty in the value of \( n_m \). Therefore, we have proposed method for control the state of these media by detecting the position of the light-shade boundary on the photodiode array [25-28].

Our studies have shown that accuracy of determination of the light-shade boundary is determined mainly by the contrast of the light-shadow boundary \( R_c \) and reliability of the adjustment algorithm of optical part of the refractometer. To increase the value of \( R_c \), we have developed and manufactured a new design of a prism from leucosapphire in the form of a trapezium with conical tips [26, 27].

The presence of this prism and the analysis of the results of our research [17, 18, 25–28] made it possible to modernize both the optical part of the refractometer and the device for processing the recorded image of reflected laser radiation. In figure 1 shows the structural diagram of the developed laboratory model of the refractometer.

![Figure 1. Structural diagram of the refractometer: 1 – semiconductor laser; 2 – optical system; 3 – prism; 4 – liquid medium flow; 5 – photodiode array; 6 – multifunctional power supply; 7 – analog-to-digital converter; 8 – processing device and control; 9 – laptop computer; 10 – device for changing the position of the semiconductor laser and optical system; 11 – device for changing the position of the photodiode array; 12 – temperature sensor; 13 – information processing unit from a temperature sensor.](image)

In the developed design the refractometer, contact with the medium flow take place only with the top face of the prism. Semiconductor laser 1 with \( \lambda = 632.8 \) nm placed in such away that its rays after the optical system 2 fall at different angles on the upper face of the prism 3 which is in contact with the medium flow. Part of the rays, the incident angle of which is more than the critical \( \alpha_c \) (figure 1), is completely reflected from the inner face of the prism and, leaving it, forms the bright part of the image on the photodiode array. The critical angle \( \alpha_c \) is determined by the following formula:

\[
\alpha_c = \arcsin \left( \frac{n_m}{n_p} \right),
\]
where $n_m$ is the refractive index of the upper layer of medium flowing in the pipeline, where $n_p$ is the refractive index of the prism’s material.

Other rays, the angle of incidence of which is smaller than $\alpha_c$, are partially refracted and pass into the liquid medium, and are partially reflected, forming the dark part of the image on the photodiode array (figure 1). In a small interval of angles from $\alpha$, the boundary between light and shadow is formed. If there are impurities in the medium or the proportion between the media changes when they are mixed, the value of $n_m$ will change. This leads to a shift in the position of the light-shadow border on the photodiode array [25-31]. The degree of contrast $R_c$ of this boundary decreases. If the temperature of the medium is known, its state can be controlled by the position of the light-shade boundary on the photodiode array. Measuring the temperature of the liquid medium $T$, it is possible to control its state by the position of the light-shadow border on the photodiode array.

To preserve the possibility of measuring this device with the refractive index $n_m$ of the liquid medium, we developed an algorithm for processing information from a photodiode array for which the program was written. After switching the instrument to $n_m$ measurement mode and its preliminary calibration, the use of this program also allowed to determine $N_m$ (for example, the relative concentration of a substance added to the aquatic environment) and the temperature coefficient $dn_m/dT$.

Calibration of the scale of the refractive index $n_c$ in the case of using for measuring the intensity of laser radiation of each sensor in the photodiode line without combining them (two, four, eight, sixteen to $Q$ - the total number of sensors) was performed on the normalized output signal $A$ from the photodiode line:

$$A = \frac{A_i}{A_{\text{max}}},$$

(2)

where $A_{\text{max}}$ is the maximum value of the illumination signal obtained on the sensor of the photodiode array, $A_i$ is the amplitude of the signal from the sensor (element) of the photodiode array, $i$ is the sensor number.

If for the measurement it is necessary to combine the sensors into larger elements, then formula (2) to normalize the signal, we propose to convert to the following form:

$$A = \frac{\sum_{i=n(p-1)+1}^{np} A_i}{A_{\text{max}}},$$

(3)

where $A_{\text{max}}$ is the maximum value of the illumination signal obtained on the combined sensor group of the photodiode line, $A_i$ is the amplitude of the signal from the sensor (element) of the photodiode cell, $i$ is the sensor number, $n$ is the number of sensors in the group, $p$ is the group number ($p$ varies from 1 to $Q/n$).

On the basis of our research, the following was established. If the center of the radiation pattern of the laser beam falls on the interface between two media at an angle $\alpha$, then the degree of contrast of the light-shadow boundary $R_c$ is maximum. The classical definition of the degree of contrast, which is used to describe the interference or diffraction pattern of laser radiation using measured maximum and minimum intensity values, is not appropriate in this situation. This is due to the absence of symmetry in the intensity distribution along the length of the photodiode array in the recorded reflected laser radiation with respect to a single maximum. The accuracy of determining its position depends on the steepness of the slopes of the intensity distribution chart along the length of the photodiode array in its vicinity. This must be taken into account when determining $R_c$. Therefore, we proposed the following formula for determining $R_c$:

$$R_c = \frac{l_1-l_2}{l_1+l_2},$$

(4)
where $I_l$ is the intensity of the laser radiation completely reflected from the lower face of the prism at a distance of 1 mm from the maximum on the photodiode array, $I_s$ is the intensity of laser radiation incident on the lower face at an angle larger than $\alpha_c$, at a distance of 1 mm on the photodiode array to the maximum.

The optical signal of the photodiode array 5 through analog-digital converter 7 is fed to the input of the processing and control device 8, assembled on the basis of the STM32 microcontroller (ARM Cortex M3 core - STM32F100RBT6B). The use of a microcontroller is justified by the fact that in an industrial device it will be necessary to realize automatic tuning of the optical system 2, as well as displaying information about the measurement results on a display device. From the output of the device 8, the signal enters the laptop, to the input of which from the information processing unit of the temperature sensor 13, also comes information about the temperature $T$ of the flowing fluid. In a laptop, based on the analysis of the data obtained, the state of the liquid flow and its other parameters are determined.

Using the reference sets of refractive index measures, the range of variation of the refractive index values $n_m$ from 1.3124 to 1.6120 was determined, which allows with the help of constructor refractometer to realize the control of flowing medium state by shifting light-shadow boundary.

Based on our studies, the following was established. In order to determine the position of the light-shadow boundary with the minimum error, it is necessary that part of the laser radiation, where this boundary is located, would fall only on one photosensitive sensor. In this case, the relative accuracy of determining the position of the light-shadow border $\Delta d$ will be determined by the following relationship:

$$\Delta d = \frac{1}{N_s}$$

(5)

where $N_s$ is the number of photosensitive sensors in the photodiode array.

For the array TSL1406RC ($N_s = 512$) array design, the $\Delta d$ value in accordance the with formula (5) is smaller than 0.002. This result makes it possible to measure the refractive index $n_m$ using (1) with the accuracy necessary to monitor their state in industrial production with the help of the refractometer design developed by us, if the liquid medium is.

If necessary, to do fundamental research using the developed design of a refractometer photodiode array with $N_s = 1024$ can be used for register laser radiation. In this case, the $\Delta d$ value will be less than $10^{-3}$.

3. Research results and discussion

Studies of different media have shown that using the design of the refractometer developed by us allows to control by the position of the light-shadow boundary biological solutions, medical suspensions, poorly transparent media (for example, wine, juices, etc.). The figure 2 shows, as an example, the intensity of laser radiation which was recorded by a photodiode array at various concentrations of sucrose $N_c$ in the flow of aqueous solution of apple juice with pulp.
Analysis of the results shows that concentration of sucrose in the flowing medium (juice) can be determined from the displacement of the light-shadow boundary with the help of calibration tables and by measuring the temperature of the flowing medium. If a crash happens in production process, then the position of the light-shadow boundary will change quickly. Using this signal one can quickly take the necessary action if know the position of the light-shadow boundary.

It should be noted that in the design of the refractometer developed by us, are preserved functional possibilities for measuring different parameters that have other types of refractometers used. For example, figure 3 shows the experimental dependences of the change in the relative density of the aqueous solution of sucrose $K_m$ in Brix units on the temperature $T$ for various concentrations of sugar. The value of $\Delta N = 0$ at $T = 293$ K is taken as the starting point for measuring the relative concentration.

The relative density of the aqueous solution was measured by the industrial refractometer PRM-100 alpha (ATAGO). The measurement inaccuracy of the device in Brix is 0.05 %. The obtained with help of laboratory refractometer and the industrial refractometer values $K_m$ coincided within the measurement inaccuracy. The results shown in figure 3 correspond with the results of measurements obtained with other types of refractometers [19, 20].
4. Conclusion
The research results showed that the method proposed by us and developed design of refractometer (with image processing algorithms) for its implementation allow to realize the condition control (by displacement of light-shadow boundary) of flowing liquid, in which the refractive index is to measure because of extremely difficult (low transparency and contain large inclusions).

It was established that of the use the new optical refractometer part design developed by us and the method for its settings to the maximum value of degree of contrast $R_c$ of light-shadow boundary allowed to reduce significantly the influence the main negative factor - temperature changes on the accuracy of medium condition control.

The use of the refractometer in our design of a new technique for adjusting the optical part using the developed image processing algorithm made it possible for a large class of liquids to obtain the maximum value of the contrast degree $R_c$ of the light-shade boundary. This made it possible to significantly reduce the impact on the accuracy of monitoring the state of the environment of the main negative factor - temperature change.

It should be noted that the refractometer developed by us can be used to flowing stream condition control of finihydrazine with $n_m = 1.6105$. This substance is used in medical industry at drugs manufacture (for example, antipyrine or amidopirin). The nowadays the of condition control of this substance in flowing.

References
[1] Nepomnyashchaya E K, Velichko E N and Aksenov E T 2016 Journal of Physics: Conference Series 769(4) 012025
[2] Marusina M Y, Bazarov B A, Galaidin P A, Marusin M P, Silaev A A, Zakemovskya E Y and Mustaev Y N 2014 Measurement Techniques 57 580-586
[3] D’yachenko S V, Kondrashkova I S and Zhernovoi A I 2017 Technical Physics 62 1602–1604
[4] Davydov V V, Dudkin V I and Myazin N S 2016 Journal of Communications Technology and Electronics 61 1159–1165
[5] Davydov V V, Dudkin V I and Karseev A Yu 2015 Russian Physics Journal 58 146-152
[6] Grevtseva A S, Smirnov K J, Davydov V V and Rud’ V Yu 2018 Journal Physics: Conference Series 1135(1) 012056
[7] Nepomnyashchaya E K, Akenov E T, Bogomaz T A and Velichko E N 2015 Journal of Optical Technology (A Translation of Opticheskii Zhurnal) 82 162-165
[8] Petrov A A, Grebenikova N M, Lukashev N A, Davydov V V, Ivanova N V, Rodygina N S and Moroz A V 2018 Journal of Physics: Conference Series 1038 (1) 012032
[9] Davydov R V, Atonov V I and Moroz A V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564378 p. 236-239
[10] Baranov M A, Velichko E N and Aksenov E T 2017 Journal of Physics: Conference Series 917(6) 062059
[11] Davydov V V, Dudkin V I and Karseev A Yu 2014 Optical Memory and Neural Networks (Information Optics) 23 170-176
[12] Davydov V V, Dudkin V I and Karseev A Yu 2014 Optical Memory and Neural Networks (Information Optics) 23 259-264
[13] Davydov V V, Dudkin V I and Karseev A U 2013 Optical Memory & Neural Networks (Information Optics) 22 112 – 117
[14] Nepomnyashchaya E K, Cheremisikina A V, Velichko E N, Aksenov E T and Bogomaz E T 2015 Journal of Physics: Conference Series 643(1) 012018.
[15] Pavlov I N, Rinkevicius B S and Tolkachev A V 2011 Measurement Techniques 53 1130-1134
[16] Shur V I, Naidenov A S and Lukin A 2006 Measurement Techniques 49 815–819
[17] Lukashev N A, Petrov A A, Davydov V V, Grebenikova N M and Valov A P 2018 Proceedings of 18th International conference of Laser Optics ICLO-2018 (Saint-Petersburg) 8435889 p. 271
[18] Davydov V V, Kruzhalov S V, Grebenikova N M and Smirnov K J 2018 Measurement Techniques 61 365-372
[19] Karabegov M A 2007 Measurement Techniques 50 619-628
[20] Leibengardt G I, Naidenov A S and Shur V I, 2014 Measurement Techniques 47 1211–1216
[21] Davydov V V and Myazin N S 2017 Measurement Techniques 60 183–189
[22] Prokof’ev A V, Pleshakov I V, Bibik E E and Kuz’min Y I 2017 Technical Physics Letters 43 194–196
[23] Fofanov Y A, Pleshakov I V, Prokof’ev A V and Bibik E E 2016 Technical Physics Letters 42 1054-1056
[24] Agruzov P M, Pleshakov I V, Bibik E E, Stepanov S I and Shamrai A V 2015 EPL 111(5) 57003
[25] Grebenikova N M, Smirnov K J, Artemiev V V, Davydov V V and Kruzhalov S V 2018 Journal of Physics: Conference Series 1038 (1) 012089
[26] Grebenikova N M, Smirnov K J, Davydov V V, Rud V Yu and Artemiev V V 2018 Journal of Physics: Conference Series 1135 (1) 012055
[27] Grebenikova N M, Myazin N S, Rud V Y and Davydov R V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564409 p. 295-297
[28] Grebenikova N M, Smirnov K J, Davydov V V and Rud V Y 2018 Journal of Physics: Conference Series 1124 (4) 041011
[29] Grebenikova N M, Davydov V V, Moroz A V, Bylina M S and Kuzmin M S 2019 IOP Conference Series: Materials Science and Engineering 497 012111
[30] Rykin E V, Moroz A V, Smirnov K J, Davydov V V and Yushkova V V 2018 MATEC Web of Conference 245 12002
[31] Myazin N S, Smirnov K J, Davydov V V and Logunov S E 2017 Journal of Physics: Conference Series 929 (1) 012080