Features of optical signals processing for monitoring the state of the flowing liquid medium with a refractometer

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Abstract. The article discusses the method of monitoring the state of flowing complex liquid media based on the phenomenon of refraction. A criterion has been defined by which the liquid medium to be measured using refraction is complex. The features of processing optical signals obtained using a refractometer from complex liquid media are considered. The results of experimental studies are presented. A comparison of the results of the experiment and the calculation is presented.

1. Introduction

Solving of problems related to improving the accuracy and reliability of monitoring the state of a flowing fluid is extremely important [1-5]. Without solving of these problems, it is impossible to improve the production automation system [5-10]. The use of automation in production, especially in the food and pharmacological industry, allows improving the quality of products and reducing its cost. This is extremely important in the conditions of tough.

In many enterprises of these industries, the control of the state of the liquid media is mainly carried out using chemical analysis in the laboratory. In a continuous process, the results of this analysis appear with a long time delay, compared, for example, with the time the fluid flows through the pipeline, etc. In some cases, they may no longer be relevant, since the “failure” in production has led to the output quality of a large batch of low-quality products. In this case, the must appropriate is the use of instruments that perform real-time monitoring of the flow state in real time [7, 8, 10-14]. Besides that the measuring elements of the devices should not introduce pollution and significant distortion in the liquid flow (change its hydraulic resistance) [2, 3, 8, 11, 12, 15-17]. This is one of the main conditions for their use in the food and pharmaceutical industry.

Therefore, the greatest preference in this situation is given to contactless measuring devices, for example, nuclear-magnetic flowmeters-relaxometers and optical meters [11, 15-22]. Other types of contactless meters (electromagnetic, ultrasonic, magnetic, etc.) do not allow monitoring the state of the medium, they can only measure the fluid flow q [10, 11]. In most cases, when automating production, to ensure the high quality of products, it is necessary to monitor the state of the technological process at several stages. Depending on the output, there can be more than 10 of them (for example, the production of juices or medical suspensions). Optical meters are simpler to operate and cost much less than nuclear magnetic ones. In addition, they can work in a large range of changes in the flow rate of the flowing liquid compared to nuclear magnetic devices [8, 18, 20-26]. Therefore, their use in this situation is more appropriate.

Among optical devices, refractometers have the greatest advantages over others [5, 8, 9, 15, 18]. When using them, no additional elements (for example, polystyrene balls) are required to be included in the liquid flow for measuring, as if takes place in optical meters based on the Doppler effect [27-29]. This allows the use of these devices for measurements in the food and pharmaceutical industry.
addition, when using them, less stringent requirements for transparency (turbidity of FNU) are imposed on media. But when using these devices to control the state of liquid flows in the food and pharmaceutical industry, a number of problems arise. One of which is associated with the processing features of optical signals reflected from the boundary of prism - liquid medium, if the liquid environment is complex. To solve this problem, you must determine these features and suggest a way to eliminate them. One of the possible solutions is proposed in our work.

2. The method of refractometry and features of registration of optical signals

The method of refractometry has one indisputable advantage over the methods that are used in other devices for measuring parameters of liquid media. Its use allows one device to monitor the state of the liquid medium, both in stationary and in the flowing state. The main parameter by which the state of the medium is monitored is the refractive index \( n_m \). Using the relation of refraction, according to the results of measurements of the refractive index \( n_m \), it is possible to determine the concentration of substances dissolved in a liquid.

The classical method of determining the refractive index \( n_m \) of the medium under investigation in refractometry is carried out through the ratio of the speeds of light in two media that are in contact with each other. If the environment consists of several components (sometimes it is called complex) and in the process of its formation the following conditions were met. There were no changes in the volume, polarizability of the components and the transparency (FNU < 15) of the medium was maintained. Then for a complex (ideal) formed system, the dependence of the refractive index \( n_m \) on the composition of the components is approximated by a linear dependence and can be described by the expression:

\[
 n_m = n_{m1}v_1 + n_{m2}v_2 \ldots
\]

where \( n_{m1}, n_{m2} \) – refractive indices of the mixture and its individual components, \( v_1, v_2 \) volume fractions of components \((v_1 + v_2 = 1)\).

In the food and pharmaceutical industry in the process often there are media with low transparency, containing large insoluble compounds (for example, apple or orange juice with pulp, etc.). It is a little incorrect to monitor their state by the measured value of \( n_m \). For such media, it is difficult to determine a single value of \( n_m \), especially in the stream, since constant mixing occurs. This creates many problems in monitoring the state of such liquid flow. In addition, the traditional method of measuring \( n_m \) with respect to the speeds of light in two media is quite difficult to apply. Since scattering and repeated reflection of laser radiation on particles of different sizes in the medium takes place [16-17, 27-31]. And if you take into account that in the liquid flow at high speeds there is a constant mixing, then these two phenomena will randomly alternate at one point in the pipeline. Therefore, these media for refractometry in a flowing fluid should be considered complex.

To control the state of the flow of complex media, we proposed a method based on the registration of the light – shadow boundary. With its implementation in the design of a refractometer, in which a prism in the form of a trapezoid, is installed some features arose. We found that they are mainly associated with ensuring a high degree of contrast of the light-shadow border in the received optical signal on the photodetector and compensation of various phenomena associated with the effect of laser beam vignetting on the prism edges.

3. The design of the refractometer and the results of experimental studies

To ensure reliable and fast monitoring of the state of liquid complex environments, taking into account the established features, we developed a new design of the refractometer. The structural diagram of its new optical part is shown in figure 1.
Figure 1. Block diagram of the optical part of the refractometer: 1 - semiconductor laser; 2 - optical system; 3 - prism; 4 - liquid fluid; 5 - photodiode array.

A fundamentally new element in this design is developed by us - prism in the form of a conical shape trapezium made of sapphire. Contact with the test medium is made only with a smaller base of this prism. Sapphire is resistant to changes in the temperature of the liquid media, to monitor the state of which a refractometer is used. This allows to ensure the main conditions for the use of instruments for monitoring the state of the medium are met: with prolonged contact of the measuring elements with the medium under study, they should not make changes in its chemical composition and physical structure [4, 5, 7, 8, 11, 18, 22].

In the new design of the optical part of the refractometer (figure 1), the laser radiation source is set so that its rays, after passing through the optical system 2, reach the smaller base of the prism 3, which is in contact with the liquid medium, at different angles. Part of the rays, the incident angle of which is larger than the critical angle $\alpha_c$ (Figure 1), are completely reflected from the inner surface of the prism and, leaving it, forms the bright part of the image on the photodiode array. The critical angle $\alpha_c$ is measured in the degrees and is determined by the following formula:

$$\alpha_c = \arcsin\left(\frac{n_m}{n_{em}}\right),$$

where $n_{em}$ is the refractive index of the prism’s material.

Other rays, the incident angle 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 varying with respect to $\alpha_c$, the boundary between light and shadow is formed. The contrast of this boundary depends on the relation between the refractive indices of the material from which the prism is made and investigated medium, as well as on the parameters of laser radiation (wavelength $\lambda$, angle of divergence $\theta$ and spatial coherence length $L_k$). In addition, the deviation in the photosensitivity values of the sensors of the photodiode array should not exceed 1% of the declared value [32, 33].

Based on our studies, 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 $\alpha_c$, then the degree of contrast of the light-shadow boundary $R_c$ is maximum. The degree of contrast $R_c$ of the recorded light-shadow boundary is determined by the following formula:
\[
R_c = \frac{I_l - I_s}{I_l - I_s},
\]

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.

At the maximum value of the degree of contrast \(R_c\), the character of the dependence of the intensity of laser radiation (3) along the length of the photodiode array changes sharply when the light-shade crosses the border. This change allows to exact a clear position of the light-shadow border. The result is achieved by moving the laser along the larger base of the prism and controlling the incident angle of the laser radiation on the side face of the prism (Figure 1). The new design of the optical part made it possible to realize this movement and change of the incident angle in the refractometer in a wider range than in previously used devices [8, 9, 15, 18].

Experiments have shown that the developed prism design allowed us to use for measurements laser radiation with a plane angle of \(\approx 22.60\), as well as to move the position of a semiconductor laser along the prism base within 10-15 mm. This feature allowed to ensure the degree of contrast not worse than 0.8. This made insignificant the effect of the feature we established on the measurement results.

In addition, the new design of the prism that we developed allowed us to use in the place where its upper face is in contact with the liquid medium, a special conical sealing gasket. This gasket makes insignificant the influence of the vignetting effect of the laser beam on the edges of the prism compared to the previously used ring-shaped gaskets in other designs of refractometers. [8, 9, 15]. The conical gasket provides greater reliability of sealing and sealing of the optical part of the refractometer. This is very important for fast fluid flows with high pressure in the pipeline.

In the new design of the optical part of the refractometer developed by us, a photodiode array TSL1406R with a length of the photosensitive layer of 38.77 mm was used to register the laser radiation. This photodiode array is placed at a short distance from the base of the prism (4-5 mm) and can freely move along it within 12 mm. This is one of the advantages of our developed design of the optical system compared to the previously used ones. The design of the photodiode array TSL1406R in front of the photosensitive layer has no focusing optical elements, as in other models of lines. Therefore, the effect of the effects associated with the repeated reflection of laser radiation between the photosensitive layer and the prism base on the degree of contrast \(R_c\) of the light-shade boundary is insignificant.

The Figure 3 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 he knows 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 [8, 9, 15, 18].

Figure 3 shows as an example the dependences of the refractive index of aqueous solutions measured by the instrument on the concentration of various media in them.

The relative density of the aqueous solution was measured by the industrial refractometer PRM-100 alpha (ATAGO, Japan). The absolute measurement error of the device is 0.0001. The obtained \( n_m \) values on the two devices coincided within the measurement error. Analysis of the results in figure 3 shows that they also agree well with the measurement results obtained earlier on stationary models of refractometers [15, 18, 34, 35].

4. Conclusion

The experiments showed that the new technical solutions developed and implemented by us in the design of the refractometer on the basis of the conducted research made it possible to make insignificant the influence of a number of negative factors related to the features of recording optical signals from the liquid medium.

The experimental results we obtained showed the following, if in the pipeline the test medium was replaced with another one, then in order for the refractometer to register minor changes in its state, it is necessary to re-calibrate the instrument. If the adjustment to the maximum of the light-shadow border is not performed (the calibration after the medium change was not done), then its position will be blurred. This is due to the fact that the dependence of the reflection coefficient on the incidence angle of laser radiation \( \alpha \) on the boundary of two media (prism – liquid) is continuous. Therefore, a sharp change in the intensity value along the length of the photodiode array without setting the instrument to a new maximum will not be observed.

Our measurements, as well as their comparison with the data obtained on other devices, showed that the manufactured new design of the optical part of the refractometer monitors the state of the liquid medium by shifting the light-shadow border in the range of variation of the refractive index values \( n_m \) from 1.3146 to 1.6120 with an error of 0.0005 in the fluid layer that borders the upper face of the prism. This measurement error is sufficient to ensure reliable monitoring of the state of the liquid environment. Modern models of refractometers, designed to monitor the state of the liquid medium, have a smaller measuring range (for example, the best of them PRM-100 alpha (ATAGO, Japan) \( n_m \) from 1.32000 to 1.55700, error 0.0001).

![Figure 3](image_url)

**Figure 3.** The dependence of the refractive index \( n_m \) of aqueous solutions of some substances on the concentration of \( N_m \): 1 - gelatin, 2 - citric acid, 3 - sucrose, 4 - ethyl alcohol.
5. References

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