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OPTICAL METHOD TO DETERMINE THE QUANTITY OF WATER IN MILK USING THE VISIBLE RADIATION RANGE

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ABSTRACT

An optical method for determine the quantity of water in milk using the visible optical radiation range is proposed. On the basis of theoretical and experimental studies of the water-milk solution spectral characteristics the proposed method mathematical model was created. The mathematical modeling of passing of the visible range optical radiation through a water-milk solution on certain thickness of the solution layer is carried out. As a result of the modeling, the dependence of the output voltage of the photoreceiver based on a pair of photodiode-operating amplifier from the relative mass fraction of milk in the water-milk solution and the wavelength of the optical radiation in the visible range is obtained.

Keywords: quantity of water in milk, visible range optical radiation, optical radiation passing.

1. INTRODUCTION

Stall milking systems, which are used for tie-stall housing system of cows, occupy almost half of the world market of milking equipment. At this systems the salary of staff is calculated according to the amount of milk they have received, because this indicator characterizes the quality of their work[1,2]. Optoelectronic methods are widely used for estimating the state of other industry processes[3,4]. Some of advanced optics measurement systems contain passive optical elements with desirable properties suitable for temperature[5], stress[6], refractive index[7] which could be useful in food industry monitoring. According to the technological regulations of the milking process, each staff has a water tank, which is necessary for the care of animals. In some cases, in order to increase the rates of milk, personnel with the help of a milking machine sucks this water into the milk pipeline. In addition, dishonest suppliers often dilute milk with water and hand it over to reception points. It is impossible to visually identify these cases, therefore, the human eye cannot distinguish water-milk solution with a small amount of water from pure milk[3]. Existing means of measuring milk parameters in most cases do not allow to carry out operative control of water availability in milk. In most cases, by their help it is impossible to identify the staff who falsifies[1,2].

Thus, the development of methods for the determine the quantity of water in milk and the creation of their mathematical models is an important and urgent task. At present, the detection of water content in milk in the laboratory is often carried out by measuring the temperature of its freezing. Such a technique is difficult to apply at the receiving points and cannot be used on stall milking systems during the process of milking[7]. In work[8] the counter of milk portions for stall milking systems with the electric conductivity sensor is considered, the principle of which is as follows. The milk portion passes through a sensor, which is a tube with built-in electrodes. The sensor generates a voltage signal that is directly proportional to the electrical conductivity value. In the presence of water in milk, the electrical conductivity of milk decreases[9], but due to the presence of foam and the absence of temperature control, it is impossible to detect a slight dilution of milk when using such sensor. Optical methods are now widely used for the determination of mixtures[10,11,12] an optical method for measuring the relative mass fraction of milk in a water-milk solution is considered. This method is based on measuring the degree of reduction of the intensity of lower range infrared radiation when it passes through the solution. The passing of the visible range optical radiation through the water-milk solution has not been studied at the present time, which determines the relevance of these studies.

Aim of the research – to create an optical method for determine the quantity of water in milk using the visible radiation range and its mathematical model.

To develop the means for determine the quantity of water in milk in the milk production process, it is necessary to make mathematical modeling of the passing of the visible range optical radiation through a water-milk solution based on its experimental passing characteristics. With the help of results of the obtained mathematical modeling it is possible to determine the optimal wavelength of the visible range optical radiation for measuring small quantities of milk in the

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water-milk solution. The development of new means of operative determine of the water in milk will allow to identify the facts of falsification of milk with water.

2. MAIN MATERIALS OF THE RESEARCH

As is well known, the weakening of monochromatic optical radiation by substance is determined by Bouguer-Lambert-Ber law

$$I(\lambda) = I_0 \cdot 10^{-k(\lambda)cd}, \tag{1}$$

where I_0 - the intensity of the radiation, that falls on the solution; $I(\lambda)$ - the intensity of the radiation that passed through the solution; d - thickness of the solution layer; c - concentration of the substance; λ – wavelength of optical radiation; $k(\lambda)$ - extinction coefficient, which is a function of the wavelength of optical radiation.

The optical density of solution determined by the expression

$$D(\lambda) = \lg \frac{I_0}{I(\lambda)} = k(\lambda)cd. \tag{2}$$

Passing through a solution of the two components, radiation by each of them is absorbed in different ways. The resulting absorption is derived by additive superposition of individual components. The optical density of two component water-milk solution is determined by the expression[13]

$$D_{VM}(\lambda) = d\left(k_M(\lambda)c_M + k_V(\lambda)c_V\right), \tag{3}$$

where $k_M(\lambda)$ - milk extinction coefficient; c_M - concentration of the milk in water-milk solution; $k_V(\lambda)$ - water extinction coefficient; c_V - concentration of the water in water-milk solution.

The relative mass fraction of milk in water-milk solution is defined as

$$\eta = \frac{m_M}{m_M + m_V}. \tag{4}$$

where m_M - mass of the milk in water-milk solution; m_V - mass of the water in water-milk solution.

In accordance to[10,11], the dependence of the optical density of the water-milk solution from the relative mass fraction of milk

$$D_{VM}(\lambda) = \frac{d\rho_M\rho_V\left(k_M(\lambda) + k_V(\lambda)\left(\frac{1}{\eta} - 1\right)\right)}{\rho_V + \rho_M\left(\frac{1}{\eta} - 1\right)}. \tag{5}$$

where ρ_M - density of milk; ρ_V - density of water.

In view of (2), after transformations we obtain

$$\frac{I(\lambda)}{I_0} = 10^{-\frac{d\rho_M\rho_V\left(k_M(\lambda)+k_V(\lambda)\left(\frac{1}{\eta}-1\right)\right)}{\rho_V+\rho_M\left(\frac{1}{\eta}-1\right)}}. \tag{6}$$

Expression (6) links the intensity of optical radiation passing through the solution with relative mass fraction of milk in solution.

At fig. 1 the experimental spectral characteristics of the water-milk solution passing (which obtained by using the spectrophotometer SF-4, $d = 10$ mm), which represent the dependence of the parameter $I(\lambda)/I_0$ at different values of η from the wavelength of the optical radiation in the visible range, are shown.

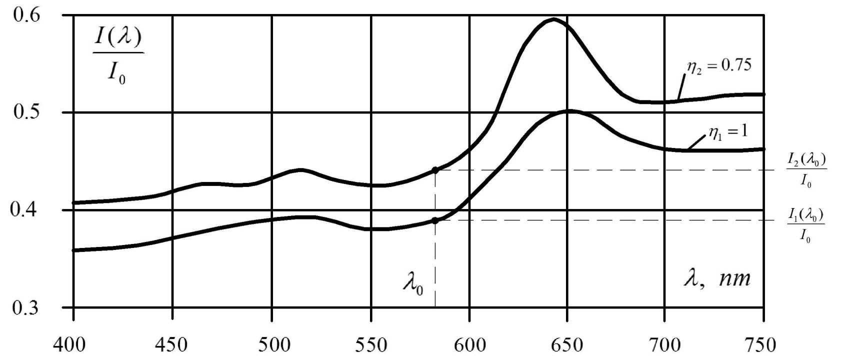

Figure 1. Experimental spectral characteristics of the water-milk solution at the visible optical range and at the different values of η.

As follows from Fig. 1, the values of the spectral characteristics vary considerably depending on the wavelength. At a wavelength of about 640 nm - 650 nm, there is a certain resonance due to the diffraction and interference of optical waves in the intervals between fat beads and strongly affects the values of the extinction coefficients.

Consider a system of two equations that determine the parameter $I(\lambda)/I_0$ at a certain wavelength λ_0 and two values of the relative mass fraction of milk in the water-milk solution $\eta_1 = 1$ and $\eta_2 = 0.75$ (see fig. 1)

$$\begin{cases} \dfrac{I_1(\lambda_0)}{I_0} = 10^{-\frac{d\rho_M\rho_V\left(k_M(\lambda_0)+k_V(\lambda_0)\left(\frac{1}{\eta_1}-1\right)\right)}{\rho_V+\rho_M\left(\frac{1}{\eta_1}-1\right)}}; \\ \dfrac{I_2(\lambda_0)}{I_0} = 10^{-\frac{d\rho_M\rho_V\left(k_M(\lambda_0)+k_V(\lambda_0)\left(\frac{1}{\eta_2}-1\right)\right)}{\rho_V+\rho_M\left(\frac{1}{\eta_2}-1\right)}}. \end{cases} \tag{7}$$

Solve this system of equations relatively to unknown values of extinction coefficients of water and milk, which are functions of the wavelength of optical radiation. After the transformations of the first expression of the system (7) we obtain an expression that correlates the extinction coefficient of milk with the extinction coefficient of water at the wavelength λ_0.

$$k_M(\lambda_0) = -\frac{\left(\rho_V + \rho_M\left(\frac{1}{\eta_1}-1\right)\right)\lg\frac{I_1(\lambda_0)}{I_0}}{d\rho_M\rho_V} - k_V(\lambda_0)\left(\frac{1}{\eta_1}-1\right). \tag{8}$$

An analogous expression is obtained after transformations of the second expression of the system of equations (7)

$$k_M(\lambda_0) = -\frac{\left(\rho_V + \rho_M\left(\frac{1}{\eta_2}-1\right)\right)\lg\frac{I_2(\lambda_0)}{I_0}}{d\rho_M\rho_V} - k_V(\lambda_0)\left(\frac{1}{\eta_2}-1\right). \tag{9}$$

Equating the right sides of expressions (8) and (9) and solving the obtained equation, we obtain the expression for the coefficient of water extinction

$$k_V(\lambda_0) = \frac{\left(\rho_V + \rho_M\left(\frac{1}{\eta_1}-1\right)\right)\lg\frac{I_1(\lambda_0)}{I_0} - \left(\rho_V + \rho_M\left(\frac{1}{\eta_2}-1\right)\right)\lg\frac{I_2(\lambda_0)}{I_0}}{d\rho_M\rho_V\left(\frac{1}{\eta_2}-\frac{1}{\eta_1}\right)}. \tag{10}$$

Substituting (8) to (10) we obtain the expression for the extinction coefficient of milk

$$k_M(\lambda_0) = -\frac{\left(\rho_V + \rho_M\left(\frac{1}{\eta_1}-1\right)\right)\lg\frac{I_1(\lambda_0)}{I_0}}{d\rho_M\rho_V} - \frac{\left(\rho_V + \rho_M\left(\frac{1}{\eta_1}-1\right)\right)\lg\frac{I_1(\lambda_0)}{I_0} - \left(\rho_V + \rho_M\left(\frac{1}{\eta_2}-1\right)\right)\lg\frac{I_2(\lambda_0)}{I_0}}{d\rho_M\rho_V\left(\frac{1}{\eta_2}-\frac{1}{\eta_1}\right)}\left(\frac{1}{\eta_1}-1\right). \qquad (11)$$

Using the expressions (11), (10) and the experimental dependences in Fig. 1 it is possible to determine the extinction coefficients of water and milk in the water-milk solution for any value of the wavelength of the optical radiation in the visible range.

Let's interpolate the experimental spectral passing characteristics, which are shown in Fig. 1, by usual cubic splines[14]

$$\frac{I_1(\lambda)}{I_0} = \begin{cases} a_{1M} + b_{1M}(\lambda-\lambda_1) + c_{1M}(\lambda-\lambda_1)^2 + d_{1M}(\lambda-\lambda_1)^3, \ \lambda \in [\lambda_1, \lambda_2]; \\ a_{2M} + b_{2M}(\lambda-\lambda_2) + c_{2M}(\lambda-\lambda_2)^2 + d_{2M}(\lambda-\lambda_2)^3, \ \lambda \in [\lambda_2, \lambda_3]; \\ \ldots \\ a_{N-1\ M} + b_{N-1\ M}(\lambda-\lambda_{N-1}) + c_{N-1\ M}(\lambda-\lambda_{N-1})^2 + d_{N-1\ M}(\lambda-\lambda_{N-1})^3, \ \lambda \in [\lambda_{N-1}, \lambda_N], \end{cases} \qquad (12)$$

$$\frac{I_2(\lambda)}{I_0} = \begin{cases} a_{1V} + b_{1V}(\lambda-\lambda_1) + c_{1V}(\lambda-\lambda_1)^2 + d_{1V}(\lambda-\lambda_1)^3, \ \lambda \in [\lambda_1, \lambda_2]; \\ a_{2V} + b_{2V}(\lambda-\lambda_2) + c_{2V}(\lambda-\lambda_2)^2 + d_{2V}(\lambda-\lambda_2)^3, \ \lambda \in [\lambda_2, \lambda_3]; \\ \ldots \\ a_{N-1\ V} + b_{N-1\ V}(\lambda-\lambda_{N-1}) + c_{N-1\ V}(\lambda-\lambda_{N-1})^2 + d_{N-1\ V}(\lambda-\lambda_{N-1})^3, \ \lambda \in [\lambda_{N-1}, \lambda_N], \end{cases} \qquad (13)$$

where a_{iM}, b_{iM}, c_{iM}, d_{iM} - coefficients of interpolating cubic splines of the experimental spectral passing characteristic $I_1(\lambda)/I_0$; a_{iV}, b_{iV}, c_{iV}, d_{iV} - coefficients of interpolating cubic splines of the experimental spectral passing characteristic $I_2(\lambda)/I_0$; $\lambda_1 \ldots \lambda_N$ - abscisses of the interpolation function nodes.

The linear photoreceiver based on a pair of photodiode-operational amplifier is widely used to measure the intensity of optical radiation[15]. In fig. 2, *a* is shown its principal scheme, and in Fig. 2, *b* is shown its equivalent scheme.

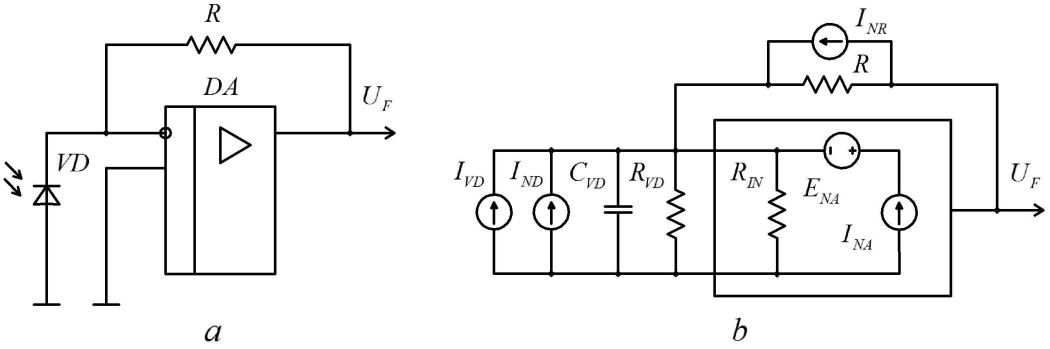

Figure 2. Linear photoreceiver based on a pair of photodiode-operational amplifier

In this photoreceiver, the VD photodiode acts as a current generator, and the DA operational amplifier converts this current into voltage. The dependence of the current flowing through the photodiode on the radiation flux is determined by the expression

$$I_{VD} = \frac{\Phi S_{I0}(\lambda)}{\sqrt{1+(\Omega\tau_{VD})^2}} - I_S\left(\exp\left(\frac{eU_{VD}}{kT}\right) - 1\right), \qquad (14)$$

where I_{VD} – photodiode current; $S_{I0}(\lambda)$ – integral current sensitivity of the photodiode; Φ – radiation flux; I_S – dark current of the photodiode; U_{VD} – voltage on the photodiode; T – absolute temperature; k – Boltzmann constant; e – electron charge; Ω – modulation frequency of the radiation flux; τ_{VD} – time constant of the photodiode, which depends on the internal resistance R_{VD} of the photodiode and its parasitic capacitance C_{VD}.

The output voltage of the photoreceiver taking into account the zero offset, the difference between the input currents, the noise voltage, is described by the expression

$$U_F = \frac{I_{VD} R}{1 + \dfrac{R}{K_0 R_{IN}} + \dfrac{1}{K_0}} + \Delta I R + U_{SM} + U_N, \tag{15}$$

where K_0 – gain factor of the operational amplifier; R_{IN} – input resistance of the operational amplifier; U_{SM} – offset voltage of operational amplifier; $\Delta \mathrm{I}$ – the difference between the input currents of the operational amplifier; R – resistance in the feedback loop of the operational amplifier; U_N – noise voltage at the output of the photoreceiver.

The value of the noise voltage at the output of the photoreceiver is affected by noise current of the resistor in the feedback loop I_{NR}, noise current of the photodiode I_{ND}, noise current of the operational amplifier I_{NA} and noise voltage of the operational amplifier E_{NA}.

With a uniform flux of optical radiation, the actual dependence is:

$$\Phi = I(\lambda) \cdot S, \tag{16}$$

where S –illuminated area of the photosensitive photodiode layer.

Substituting (14) and (16) into (15), after transformation we obtain

$$U_F = \frac{R \cdot S \cdot I(\lambda) \cdot S_{I0}(\lambda)}{\left(1 + \dfrac{R}{K_0 R_{IN}} + \dfrac{1}{K_0}\right)\sqrt{1 + (\Omega \tau_{VD})^2}} - \frac{I_S R \left(\exp\left(\dfrac{e U_{VD}}{kT}\right) - 1\right)}{1 + \dfrac{R}{K_0 R_{IN}} + \dfrac{1}{K_0}} + \Delta I R + U_{SM} + U_N. \tag{17}$$

If the light flux is not modulated, then the effect of the frequency properties of the photodiode can be neglected. If $U_F \gg U_{SM}$ and $I_{VD} \gg \Delta I$, values U_{SM} and ΔI can be neglected. When using an elemental base with low noise, the noise component U_N can be neglected. Due to the small value of the dark current, we can assume that $I_S \approx 0$.

Input resistance of modern operating amplifiers is very high, the gain factor of modern operational amplifiers is also very high, thus

$$\lim_{\substack{K_0 \to \infty \\ R_{IN} \to \infty}} \left(1 + \frac{R}{K_0 R_{IN}} + \frac{1}{K_0}\right) = 1. \tag{18}$$

Taking into account all these conditions, the expression (17) will look like

$$U_F = I(\lambda) \cdot S_{I0}(\lambda) \cdot R \cdot S. \tag{19}$$

Taking into account expression (9), expression (19) takes the form

$$U_F = I_0 \cdot S_{I0}(\lambda) \cdot R \cdot S \cdot 10^{-\frac{d \rho_M \rho_V \left(k_M(\lambda) + k_V(\lambda)\left(\frac{1}{\eta} - 1\right)\right)}{\rho_V + \rho_M \left(\frac{1}{\eta} - 1\right)}}. \tag{20}$$

Thus, we obtain the dependence of the linear photoreceiver output voltage from the relative mass fraction of milk in the water-milk solution is determined by the expression[10,11]. After measuring the intensity of light radiation that passed through the water-milk solution, it is possible to determine the relative mass fraction of milk in the water-solution in terms of expression[12]

$$\eta = \frac{\rho_M \lg \dfrac{U_F}{I_0 \cdot S_{I0}(\lambda) \cdot R \cdot S} + d \rho_M \rho_V k_V(\lambda)}{(\rho_M - \rho_V) \lg \dfrac{U_F}{I_0 \cdot S_{I0}(\lambda) \cdot R \cdot S} + d \rho_M \rho_V \left(k_V(\lambda) - k_M(\lambda)\right)}. \tag{21}$$

For mathematical modeling in accordance to expressions (10) - (13) and (20), a package of mathematical applications Maple 9[16] was used. The result of the mathematical modeling of the linear photoreceiver output voltage dependence from the relative mass fraction of milk in the water-milk solution and the wavelength of the optical radiation in the visible range is shown in Fig. 3. and Fig. 4.

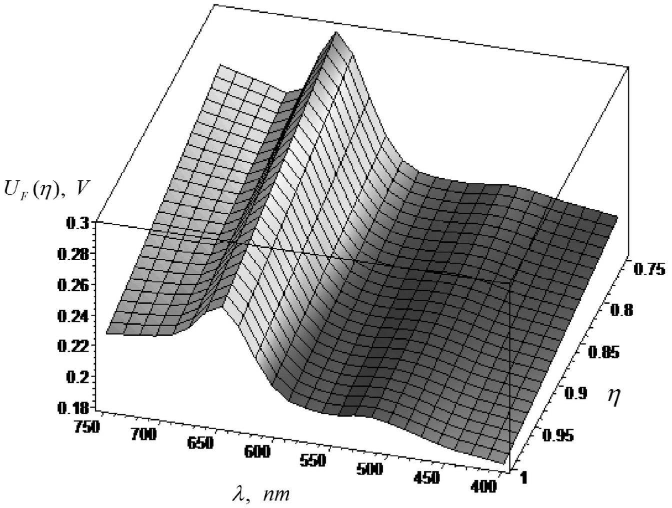

Figure 3. Dependence of the linear photoreceiver output voltage from the relative mass fraction of milk in the water-milk solution and the wavelength of the optical radiation in the visible range.

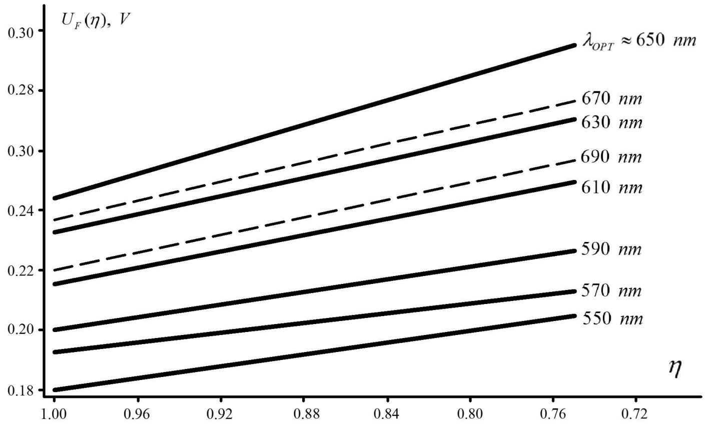

Figure 4. The family of dependencies of the linear photoreceiver output voltage from the relative mass fraction of milk in the water- milk solution at different values of the wavelengths at the visible range optical radiation.

The modeling was carried out in the visible optical radiation range for wavelengths from 400 nm to 750 nm and the range of relative mass fraction of milk in the water-milk solution from 0.75 to 1 and $d = 10$ mm. During the modeling, it was assumed that the integral sensitivity of the photodiode is constant throughout the wavelength range. The choice of the relative mass fraction of milk range in the water-milk solution is due to the fact that, according to the authors' observations, with $\eta < 0.75$ the human eye begins to distinguish between water and milk solution from pure milk. As it follows from Fig. 4, there is an optimal wavelength ($\lambda_{OPT} \approx 650$ *nm* if $d = 10$ mm), in which the sensitivity of the measuring channel of the relative mass fraction of milk in the water-milk solution will be maximal.

CONCLUSIONS

An optical method for determine the quantity of water in milk using the visible optical radiation range is proposed. On the basis of theoretical and experimental studies of the water-milk solution spectral characteristics the proposed method mathematical model was created. The mathematical modeling of passing of the visible range optical radiation through a water-milk solution is carried out. As a result of the modeling, the dependence of the output voltage of the photoreceiver based on a pair of photodiode-operating amplifier from the relative mass fraction of milk in the water-milk solution and the wavelength of the optical radiation in the visible range is obtained. Depending on the thickness of the water-milk solution layer, there is an optimal wavelength of visible range optical radiation, at which the sensitivity of the measuring channel of the relative mass fraction of milk in the water-milk solution will be maximal. Promising is the use of the proposed mathematical model for the creation of means for measuring the relative mass fraction of milk in the water and milk solution to detect the facts of milk falsification.

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