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Optical sensor of harmful air impurity concentration

Abstract. *It is shown that to solve the problem of ensuring acceptable sanitary conditions in livestock premises while minimizing energy costs, it is advisable to use an automated exhaust ventilation system with control over the contour of the allowable concentration of harmful atmospheric impurities. The proposed block diagram of the sensor concentration of harmful impurities in the air, suitable for operation in conjunction with an automated ventilation system. Its mathematical model and transformation equation are obtained. It is shown that in the measurement range, which corresponds to the change of controlled impurities in the range from zero to the maximum allowable concentration, the static characteristic of the proposed sensor can be approximated by a linear function without significant additional methodological error.*

Streszczenie. *Wykazano, że w celu rozwiązania problemu zapewnienia akceptowalnych warunków sanitarnych w pomieszczeniach inwentarskich przy jednoczesnym zminimalizowaniu kosztów energii wskazane jest zastosowanie automatycznego systemu wentylacji wyciągowej z kontrolą konturu dopuszczalnego stężenia szkodliwych zanieczyszczeń atmosferycznych. Proponowany schemat blokowy czujnika stężenia szkodliwych zanieczyszczeń w powietrzu, przystosowany do współpracy z z systemem wentylacji. Wykazano, że w zakresie pomiarowym, który odpowiada zmianie kontrolowanych zanieczyszczeń w zakresie od zera do maksymalnego dopuszczalnego stężenia, charakterystykę statyczną proponowanego czujnika można aproksymować funkcją liniową bez znacznego dodatkowego błędu metodologicznego.* (***Optyczny czujnik stężenia szkodliwych zanieczyszczeń w powietrzu***)

Keywords: measurement, harmful impurities, air, optical measurement method.
Słowa kluczowe:.czujnik zanieczyszczenia powietrza, kontrola zanieczyszczenia powietrza

Introduction

Today, the effective functioning of farms in modern conditions requires development and implementation of technologies that meet international standards and reduce excessive energy losses [1, 2].

At their location places, animals inevitably generate harmful gases, among which carbon dioxide, ammonia and hydrogen sulfide are the most typical ones. Maximum permissible concentrations of these impurities in the atmosphere of livestock facilities are strictly regulated, and their excess can not only cause the deterioration in the animals' productivity, but also their mass death [3].

Arrangement of a forced exhaust ventilation system represents a typical approach to solving the problem of such atmospheric impurities' excessive concentration. However, operation of ventilation systems requires a significant power consumption, the amount of which is proportional to its performance. And this is the winter season, when this problem is especially acute: on the one hand, the rate of contaminants' generation increases due to the animals' being held indoors permanently, and on the other hand – the ventilation system's operating costs are complemented by the costs of the living area's heating, which also increase with the growth in the productivity of the latter [4, 5].

In view of the foregoing, apparent is the need to maintain the atmospheric concentration of these contaminants at a certain "optimal" level. And since the ability to ensure an optimal concentration of these impurities is significantly limited today by the lack of high-precision concentration sensors suitable for long-term real-time operation as part of an automated ventilation control circuit [6, 7], one can state for sure that designing of such sensors is a relevant research and application-related task.

Setting the task

Calometric, nephelometric, photometric and others are the most common methods for laboratory analysis of air samples containing harmful gases [8].

The calometric method is the most common and accurate one, which consists in generation of solutions stained with a harmful gas, followed by assessment of the degree of light flux solution's absorption with a photoelectrocalorimeter [9]. The nephelometric method consists in determining the intensity of sediment formation after investigated harmful gas's interaction with certain chemicals.

To solve this problem, it is necessary to measure the concentration of impurities on real-time basis. Therefore, the use of chemical-based methods is impractical [10]. Hence, as a basic method for implementation of harmful impurities' concentration sensor to be suitable for use in conjunction with the automatic system of monitoring the livestock premises' ventilation, the use of an optical method [11] of measuring the concentration is proposed. This method will ensure an intermediate measurement of attenuation of transmitted electromagnetic wave's amplitude, the frequency of which is going to correspond to the investigated impurity's absorption band.

Analysing the ways of problem solution

To implement this task, an optical sensor for concentration of harmful impurities is offered, the block diagram of which is shown in Fig. 1.

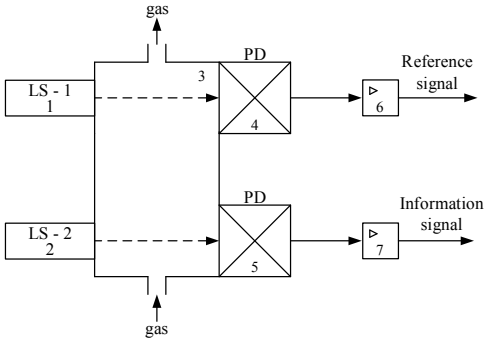

Fig.1. Block diagram of the optical sensor for harmful impurities' concentration

The device operates as follows. The first radiation source 1 emits a narrow- spectrum optical beam that does not correspond to the absorption lines of the analyzed gas's components. The second radiation source 2 emits a narrow-spectrum optical beam corresponding to the absorption lines of the analyzed gas's components. Passing through shielded cuvette 3, the rays from the output of the first 1 and the second 2 radiation sources fall on the inputs, respectively, of the first 4 and second 5 photodetectors. Cuvette 3 is filled with the test gas (which can be pumped forcibly or be introduced by natural convection).

The light beam from the exit of the first radiation source 1, when passing through cuvette 3, will be attenuated due to non-absolute transparency of the test gas. Hence, the transparency ratio of the test gas's optical medium can be determined as follows:

(1) $$\alpha = \frac{F_1}{F_0},$$

where F_0 is the luminous flux of the beam at the output of the first 1 and second 2 radiation sources; F_1 – the ray's luminous flux at the input of the first photodetector 4.

When passing through cuvette 3, the light beam from the output of the second radiation source 2 is additionally (not accounting for the test gas's transparency) attenuated in accordance with Bouguer-Lambert-Beer's law:

(2) $$F_m(c) = F_0 e^{-\varepsilon c d},$$

where F_m – is the theoretical light beam at the entrance of the second photodetector 5; ε - is the molar monochromatic absorption coefficient; c – is the molar concentration; d is the distance traveled by the beam.

Given that the beam from the second radiation source 2 will also suffer attenuation through the environment's non-absolute transparency, the actual light output beam at the second sensor's entrance 5 will be calculated as follows [12]:

(3) $$F_2(c) = \alpha F_0 e^{-\varepsilon c d}.$$

In the first 4 and second 5 photodetectors, the intensity of the luminous flux is converted at the level of direct voltage supplied, respectively, to the inputs of the first 6 and the second 7 normalizing amplifiers [13, 14], where they are amplified to the level suitable for further analysis.

It is proposed to use a connected pair of photodiode-operational amplifiers as photodetectors. Fig. 2 shows its electrical schematic diagram, and Fig. 2 – its equivalent substitution scheme.

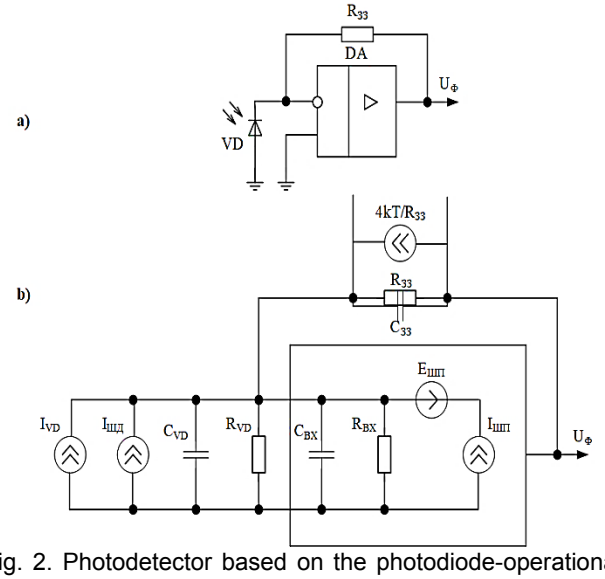

Fig. 2. Photodetector based on the photodiode-operational amplifier's pair

In this circuit, VD photodiode acts as a current generator, and operational amplifier DA [14] converts this current into voltage. The dependence of the current that flows through the photodiode on the irradiation flux is described by expression [15].

(4) $$I_{VD} = \frac{FS_{I0}}{\sqrt{1+(\omega\tau_{VD})^2}} - I_S\left(e^{\frac{e_e U_{VD}}{kT}} - 1\right),$$

where I_{VD} is the photodiode's current; S_{I0} – the photodiode's current sensitivity to selected irradiation spectrum; F is the luminous flux; I_S –is the photodiode's dark current; U_{VD} – the voltage drop on the photodiode; T – the absolute temperature; k is the Boltzmann constant; e_{ee} is the electron charge; $\dot{\omega}$ is the cyclic frequency of the modulated irradiation flux; τ_{VD} is the photodiode's temporal constant, which depends on the values of R_{VD} photodiode's internal resistance, C_{VD} photodiode's parasitic capacitance and Dissemination and minority charge carrier's discharge time.

That said, the output voltage of the photosensor of proposed design, considering the noise voltage, zero offset and the difference of input currents may be described as [16]:

(5) $$U_{\Phi} = \frac{I_{VD}R_{33}}{1+\frac{R_{33}}{KR_{BX}}+\frac{1}{K}} + \Delta I \cdot R_{33} + U_{3M} + U_{Ш},$$

where K is the operational amplifier's transmission factor; R_{BX} – the operational amplifier's input impedance; U_{3M} – operational amplifier's zero bias voltage; ΔI – the difference between the operational amplifier's input currents; $U_{Ш}$ – the noise voltage at the photodetector's output.

The output voltage module of noise is determined by expression [17, 18]:

(6) $$U_{Ш} = \sqrt{E_{ШП}^2 + (I_{ШП}^2 + I_{ШД}^2 + I_{33}^2)R_{33}},$$

where $E_{ШП}$ is the operational amplifier's noise voltage spectral density; $I_{ШП}$ is the operational amplifier's noise current spectral density; $I_{ДШ}$ is the photodiode's noise current spectral density; I_{33} is the feedback connection's noise current resistance spectral density.

Photodiode's noise current density that operates in fotovoltaic mode [18]:

(7) $$I_{ШД} = \sqrt{\frac{4kT\Delta f}{R_{VD}}},$$

where Δf is the effective band of electron path transmission.

The density of feedback connection's noise resistance current [18, 19]

(8) $$I_{33} = \sqrt{\frac{4kT\Delta f}{R_{33}}}.$$

Taking into account the diode's and operational amplifier's mathematical models given in [20], (6) expression can be represented as follows:

(9) $$\dot{U}_{\Phi} = \frac{\frac{FS_{I0}K_0R_{BX}R_{33}}{1+j\omega\tau_{VD}}}{K_0R_{BX}+R_{33}+R_{BX}-\frac{\omega^2R_{BX}R_{33}(C_{BX}-C_{33})}{\omega_{TP}}+ +j\omega\left(\frac{(R_{33}+R_{BX})}{\omega_{TP}}+R_{BX}R_{33}(C_{BX}+C_{33}(K_0+1))\right)}.$$

where K_0 is the operational amplifier's transmission factor at zero frequency; $\dot{\omega}_{TP}$ is the operational amplifier's maximum cyclic frequency.

In most cases, the photodiode's cutoff frequency is much lower than the operational amplifier's cutoff frequency [19, 21]. Therefore, the frequency response decrease in the high frequency range is determined by the photodiode's frequency properties. This makes it possible to ignore the parasitic capacitance's influence in the feedback circuit and the operational amplifier's input capacitance. The input resistance of modern operational amplifiers is tens of MOhms, which is much higher than the resistance in the feedback circuit and the photodiode's internal resistance [8]. Therefore it is possible to assume $R_{BX} = \infty$. Provided that the

irradiation frequency is much lower than the photodiode's cutoff frequency, its frequency properties can be neglected.

Given the above, (6) expression can be simplified:

$$U_{\Phi} = S_{I0} R_{33} F. \tag{10}$$

The linear dependence of the photodetector's output voltage on the luminous flux follows from (7) expression, which is the photodetector's simplified mathematical model based on a photodiode-operational amplifier pair. All the above assumptions are valid in our case, because the impurities' concentration cannot change instantly, and therefore the equivalent frequencies of the photodetector's output signal alternation will be quite low. Hence, by substituting (3) into (7) we will obtain:

$$U_{\Phi}(c) = S_{I0} R_{33} \alpha F_0 e^{-\varepsilon c d}. \tag{11}$$

Dependence (8) unambiguously connects the input and output values of proposed harmful impurities concentration optical sensor, being its conversion equation.

To obtain the proposed sensor's static characteristics, let us imagine the sensor's typical technical parameters: the photodiode's current sensitivity to selected radiation spectrum – 0.05 A/W, feedback resistance – 1kOhm, test gas's optical medium transparency coefficient – 0.8, the beam's luminous flux at the radiation source output – 0.1W, molar monochromatic absorption coefficient – 300 l/(mol·cm), the distance traveled by the beam – 20 cm, the molar concentration range – from 0 to 10^{-4} , which roughly corresponds to volume concentration alteration range from 0 to 0.25% (maximum allowable carbon dioxide concentration in the livestock premises [1]). The static characteristics of the proposed sensor with the specified technical parameters are presented in Fig. 3.

As follows from Fig. 3, proposed sensor's static characteristic at selected technical parameters and specified measurement range is of a quasi-linear nature. The linearity of the sensor's static characteristics, in the general case, allows greatly to simplify the obtaining of the resulting transformation equation of the measuring instrument built on its basis. However, the linearization of quasi-linear dependence inevitably leads to increase in the methodological error [19, 22].

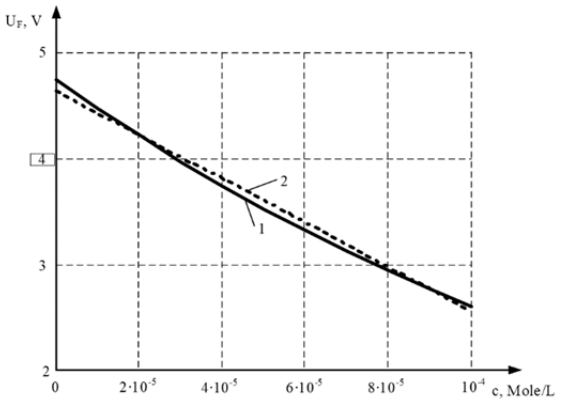

Fig. 3. Static characteristics of proposed contaminants concentration optical sensor :1 – derived from (11); 2 – linearized

Hence, to establish the feasibility of the obtained static characteristic's linearization, we will analyze the value of the additional methodological error that will be introduced as a result of linearization based on known relative measurement error's dependence:

$$\delta_{\partial}(c) = \frac{\left|U_{\Phi Л}(c) - U_{\Phi}(c)\right|}{U_{\Phi}(c)} \cdot 100\% \tag{12}$$

where $U_{\Phi Л}(c)$ is the linearized dependence of voltage at the photodetector's output on the investigated impurity's molar concentration.

The results of modeling the dependence between relative linearization error and investigated impurity's molar concentration are shown in Fig. 4.

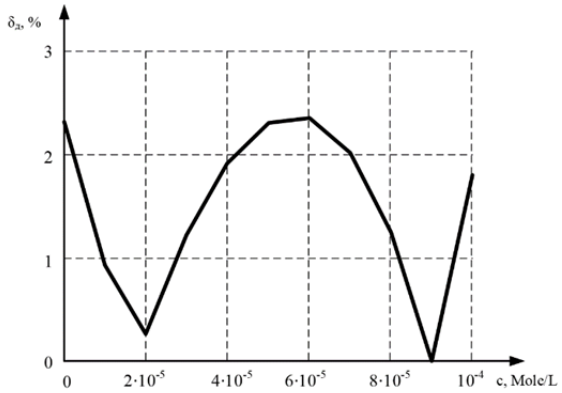

Fig. 4. Dependence between relative linearization error and investigated impurity's molar concentration

As follows from Fig. 4, the optical sensor's given values providing for acceptable sensitivity do not exceed 2.5%.

Conclusion

1. Proposed was the design of the harmful air impurities' concentration optical sensor, which operation principle is based on application of Bouguer- Lambert-Beer effect suitable for operation in conjunction with an automated ventilation system.
2. Developed was the mathematical model of proposed sensor, on which basis the transformation equation was obtained. It has been demonstrated that within the measurement range, which corresponds to the change in controlled impurities ranging from zero to the maximum allowable concentration, the proposed sensor's static characteristic may represent an approximated linear function. The additional methodological error to be introduced due to linearization of the sensor's specified parameters does not exceed 2.5%.

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