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Flammable gases and vapors of flammable liquids: Monitoring with infrared sensor node[☆]

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ABSTRACT

A high number of gas leaks occur every year at the industrial facilities. It may lead to diseases, deaths, damage of equipment and ecological incidents. We present the optical absorption infrared sensor for monitoring of the lower explosive limit of gases and vapors containing flammable hydrocarbon compounds, and the description of the sensor design and characteristics. The sensor is able to monitor up to 30 components and can be interfaced with an external device using MODBUS RTU protocol. Our design opens up wide opportunities for the indoor and outdoor gas monitoring applications for the petrochemical and oil processing industries and hazardous industrial facilities.

1. Introduction

The problem of monitoring the lower explosive limit (LEL) of flammable gases and vapors of flammable liquids is the task of top priority for gas-and-oil industry, e.g. transportation and storage of gas and oil products. Explosion-hazard areas located near boiler facilities and processing stations are of particular significance for monitoring and require the reliable and high-precision measuring instruments with time-stable technical characteristics: the leak not detected in time may cause grave damages [1].

Catalytic [2], semiconductor [3] and optical [4] sensors are extensively used to monitor LEL of flammable gases and vapors of flammable liquids. The essential fault of these sensors is the ambiguous value of relative sensitivity coefficient between the calibration component, e.g. methane, and the measured component (flammable gases and vapors of flammable liquids) within the full measuring range. The disadvantage of the approach is that this value is defined during the sensor adjustment at a single point of the sensor output characteristic. The limitation of the maximum permissible intrinsic and complementary errors using the calibration component does not provide the end user with the sufficient information on the combined error of the measuring instrument when detecting the measured component. Besides that, the outdoor environment, industrial applications impose a number of high demanding requirements to catalytic and semiconductor sensors, e.g. sensitivity, selectivity, reliability, which can hardly be satisfied at a time [14,15].

We note that, unlike catalytic and semiconductor sensors, the optical sensors based on non-dispersive infrared (NDIR) technology [8] have a number of advantages in terms of high zero stability, sensitivity, selectivity, high speed of response, resistance to corrosive atmospheres and to elevated concentrations of monitored and assist gases, and the ability to operate in anoxic environment.

This paper presents the experimental results of research and development work on the parameters of the optical absorption infrared sensor for detecting LEL of flammable gases and vapors of flammable liquids in gas-and-oil industries. The primary goal of this work is to design the sensor node which is capable of monitoring up to 30 components (the catalytic or semiconductor sensor nodes typically monitor one or two hazardous gases at a time [9]) and which has the individual limitation of maximum permissible intrinsic error for each measured component and limitation of the maximum permissible complementary error for measured components under actual operating conditions (operating temperature, pressure, humidity).

The remainder of this paper is organized as follows. In Section 2 we review some of the state-of-the-art solution relevant to the problem. Our approach is presented in Section 3, where we

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first make the system overview and after that describe it in more details. The experimental results are shown in Section 4, in which we describe the preparation of the experiment and then focus on the actual results. Finally, we conclude in Section 5.

2. Related work

The gas leak detection systems used in industry can be divided into two categories: the fixed instrumentation and mobile detectors. The fixed instrumentation, such as the gas detectors, are typically installed nearby the source of a potential leak, e.g. the valve, storage, compressor. The systems of this kind are wired in a network and have a constant power source. Upon detecting a leak they generate an audio or visual alarm or send an alarm message to an operator over the network.

The recent trend in detecting gas leaks is the application of the wireless sensor network (WSN) paradigm [9]. The WSN consists of a number of wireless sensor nodes with sensing, processing and wireless communication capabilities organized in a wireless network. Both WSN and wired methods have their advantages and disadvantages. WSN technology, for instance, does not require any cable production, which makes this approach flexible in terms of the nodes deployment, debugging and maintenance. This feature is of particular significance for the industrial facilities where the sensors have to be installed at various heights, within difficult to access areas and to cover large space. The avoidance of cabling helps save extra money for the monitoring tools: the cost of a cable and a sensor device is in most cases equivalent. However, the ‘wired’ approach ensures constant monitoring due to the availability of a power source. WSN devices, in contrast, spend most of the time in the sleep mode. Indeed, the high power consumption of gas sensors (up to 600 mW) prevents the ubiquitous deployment of WSN solutions for hazardous gases monitoring. Besides, wired sensors have much more reliable communication as compared with WSN devices which are the subject to interference and for which the close location to each other does not guarantee a reliable wireless link [10].

Mobile detectors are typically hand-held devices which have to be moved to a suspected leak source. Following this approach, a worker is supposed to evaluate the sensor readings in real time and even to trace the leak to its source. WSN and wired approaches make it possible to avoid this risky for the worker situation and to secure the safer detection of leaks [11].

Next we discuss some of the state-of-the-art platforms for gases detection. Video monitoring using cameras has become popular for gas leaks and potential fire detections [24,25]. The cameras are usually mounted on a pre-defined height and often rotate to ensure the coverage of the entire space of interest. The devices take the snapshots of the environment and perform the analysis of the images to identify gas leaks. Similar to ours approach is presented in [19] where infrared laser spectroscopy is used for detection and quantification of numerous gas species at part-per-million to part-per-billion (ppm–ppb) concentrations. The authors report on the WSN platform able to detect twelve components. The major drawback of this design is the high power consumption which makes the system practically useless as an autonomous monitoring device. Another ‘energy-aware’ design is based on the film (colorimetric) gas sensors [20,21]. This approach is based on film color change in the presence of detected components. The designs of this kind are characterized by low power consumption (around 3 mW) and long sensor response time (up to 5 min) which fails to meet safety requirements. The viable trade-off between the first and the second solutions is the application of catalytic sensors which have good sensitivity and selectivity as well as the adequate power consumption for their usage in WSN applications [10,22]. However, apart from the negative features mentioned in introduction to this article these sensors require extra techniques to improve their stability [23] at changing ambient temperature [26] and humidity [27] as well as high detected gas concentrations to avoid ‘carbonization’, e.g. during the sensing of high concentrations of methane.

3. Optical sensor design

In this section, we first overview the proposed solution and after that focus on the platform design in more details.

3.1. *System overview*

The operating principle of the optical absorption sensor is based on the registration of changes in the intensity of radiation interacting with a gaseous medium under test at the wavelengths characteristic of this medium. The identification of wavelength operating range in broadband spectrum of the emitter is performed using interference filters (we discuss the selection of the wavelength later in Section 4.2). During the development of the sensor node capable of monitoring up to 30 components the conventional structure of the primary measuring transducer is complicated by the requirement of detecting such a wide range of substances with the essentially different spectral characteristics. It is necessary, therefore, to solve the problem of combined optimization of spectral characteristic parameters of interference filters and selective reflector (λ, τ) [5,6] of optical system, and the element construction of optical channel of the sensor (L) [7].

The block diagram and the sensor (in this work we apply to our design “sensor” and “sensor node” interchangeably) prototype are shown in Fig. 1. The sensor node has compact design (see Fig. 1b) and can be easily interfaced with the external devices and the gas leak systems. The architecture of IR sensor node includes the following main blocks: *the emitting source*, *the radiation receiver*, *the selective reflector* and *the processing and communication unit*. The optical circuit of the sensor is based on a two-channel measurement circuit with the use of operating (measuring) and reference (comparative) channels.

The sensor is supplied by the DC source with the supply voltage of 5 ± 0.2 V. The average current consumption is 125 mA. This value enables us to apply the WSN paradigm equipped with the energy scavenging technology [18] to next upgrades. In this case an energy-aware design for WSN is the task of top priority [16,17].

3.2. *Platform design*

In this section we focus on the main blocks of the sensor node. The circuit schematic of sensor node based on the IR sensor is shown in Fig. 2.

Emitting source is a mini infrared lamp with a wide spectral range of radiation. The feature of the lamp operating mode is a modulation of luminous flux with a frequency generated by the micro processing unit, $D2$, using the switch.

Switch is built on MOSFET $VT1$ which supplies modulated voltage signal to the lamp which generates the modulated emission. The presence of this emission is the obligatory condition for generating the potential difference on a pyroelectric crystal. Fig. 3 shows an example of the oscillogram where the frequency of modulated signal generated by $VT1$ is 0.8 Hz (1.2 s). This oscillogram is measured on $R6$ which is a precision resistor of 1 Ω. The signal from this resistor is conducted to the MCU for controlling the flowing current. The signal average amplitude is 115 mV. We measure $R6$ voltage drop and compute the flowing current, i.e. current consumption, using Ohm’s law. The current consumption of the lamp is 115 mA. The lamp voltage supply is 5 V which results in the power consumption

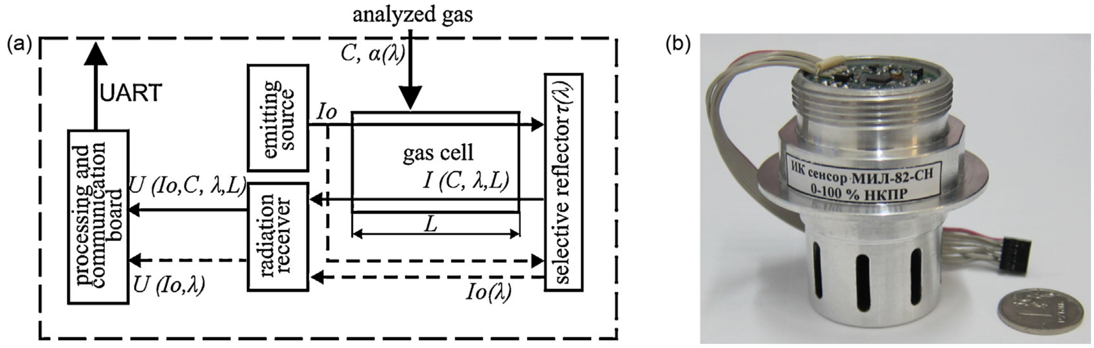

Fig. 1. (a) Sensor node block diagram. (b) Sensor node prototype.

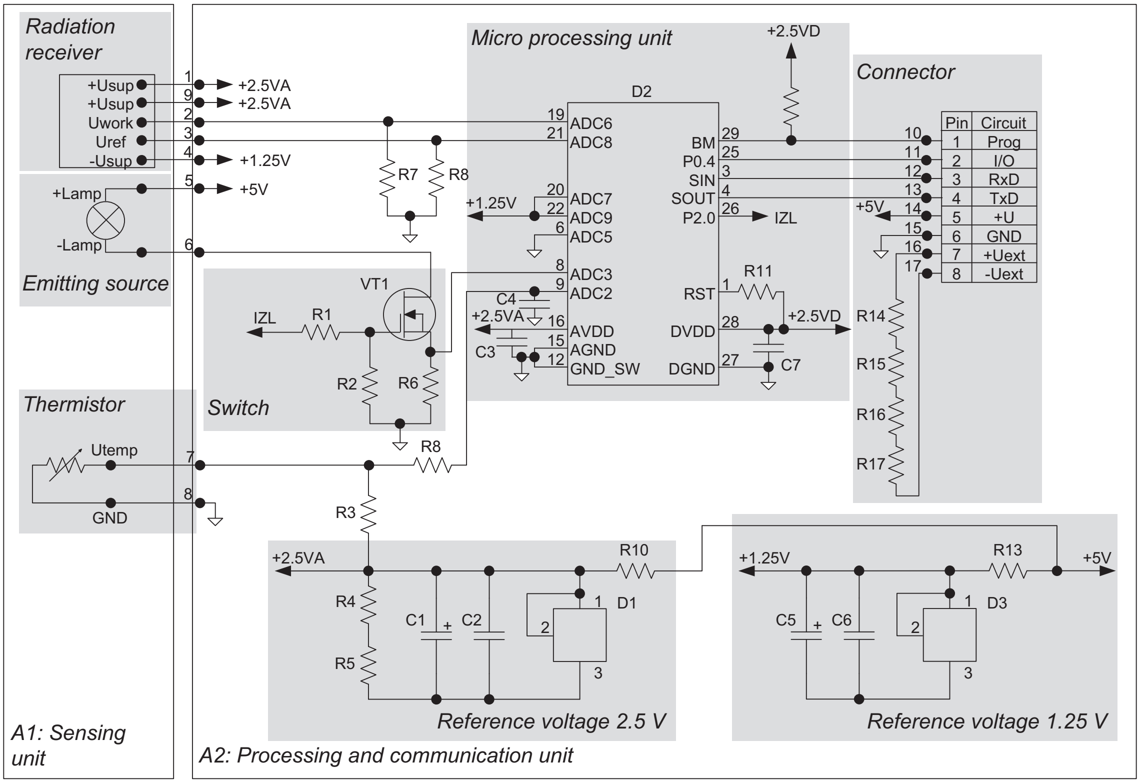

Fig. 2. Sensor node platform.

($P = U{\cdot}I$) of 575 mW. If the modulation duty cycle is 50%, the average power consumption is 287.5 mW.

Radiation receiver is a high-sensitivity two-channel pyroelectric detector with the integrated interference filters that have specific spectral characteristics. The design and technical characteristics of the detector allow its exploitation in a temperature range from −60 °C to +90 °C. The application of the temperature compensated crystal helps exclude a signal ripple and provides the stable output signals of the pyroelectric detector at a high rate of change in ambient temperature. We used a pyroelectric detector (PYS) by Perkin Elmer as a radiation receiver.

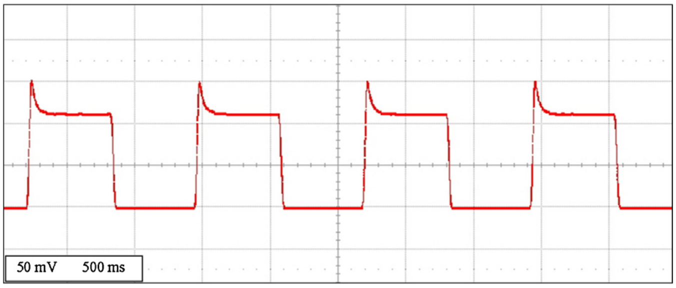

Fig. 3. Oscillogram of modulated signal, 0.8 Hz (1.2 s).

Selective reflector, which is, in fact, an interference filter applied to a spherical quartz substrate, performs the adjustment of spectral range of probe radiation coming from the emitting source. Therefore, the selective reflector to some extent is a regulating element.

Processing and communication unit performs the functions of processing the input signals from the pyroelectric detector, measuring temperature, controlling the emitter, saving the sensor parameters, and also generating signals of interface channel. The unit is built on the microcontroller Aduc7061, *D*2. The measured values are communicated to the external devices via UART interface of microcontroller using MODBUS RTU protocol

With the integrated circuits *D*1 and *D*3, the 2.5 V and 1.25 V *reference voltage* is generated.

The sensor temperature is controlled using NTC *thermistor*, *t*. During the operation at low ambient temperature which exceeds an acceptable threshold of the microcontroller *D*2, reference voltage generators *D*1 and *D*3, the sensor node can automatically increase the temperature near these integrated circuits to improve their working conditions using *R*14–*R*17 chain. These resistors work as the heating dissipation elements which are installed on the back of the board and under the electronic components sensitive to low temperatures. The heating works as follows: upon receiving the information about the low temperature from the thermistor, an external voltage 6 V is supplied to contacts 7 and 8 of the connector. The 'heating' current in this case is 150 mA.

3.3. *System operation*

A probe radiation I_0 passes through the gas cell with the analyzed component with length *L*, reflects from the selective reflector, and comes to the two-channel pyroelectric detector. Signals from operating (*U*) and reference channels (U_0) of pyroelectric detector are digitized by means of analog-to-digital converter (ADC) in the microcontroller.

After that the digital band-pass filters select the signals on modulation frequency from the pyroelectric detector signals without noise. These signals are rectified by a phase-independent rectifier, and a signal constant component is selected by a digital low-pass filter.

The obtained signal difference between the operating and reference channels is a measure of component content in the analyzed sample. In order to provide the required metrological characteristics under the higher and lower temperatures, the corrections are applied. After that the sensor conversion characteristic is linearized, and the value of measured concentration of detected component in the analyzed gas is obtained. The value of measured concentration is converted into a signal of UART interface which makes it possible to generate a communication channel between the sensor node and a PC or other external devices by MODBUS RTU protocol.

The evaluation of the sensor sensitivity, the determination of metrological characteristics, and rating of the sensor parameters for monitoring pre-explosive concentrations of flammable gases and vapors of flammable liquids can be conducted with various types of metrological support. For the monitoring of gaseous component concentrations we used the metrological support called "state standard sample – test gas mixture" (SSS-TGM). The estimation of liquid substances and rating of sensor parameters require special test facilities, e.g. a calibration chamber, for preparing certified air–vapor mixtures.

Data on output characteristics and correction coefficients for measured components obtained using the calibration chamber, or SSS-TGM in the case of monitoring of gaseous component concentrations are saved in the nonvolatile memory of the sensor. The type of the measured component to monitor its pre-explosive concentrations is selected by a user with the service software installed on the PC. It should be emphasized, however, that rating of the sensor's metrological characteristics for the measured component must be performed using the selected measured component and not the calibration component, as it happens in most cases.

4. Experimental results

In this section we present our experimental results. We start this section with the description of the preparation of the experiments and then describe the actual results.

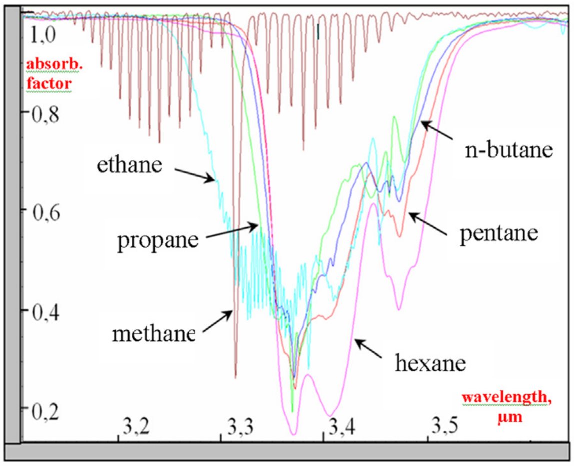

Fig. 4. Absorption spectrum of hydrocarbons.

4.1. *Preparation of experiment*

In the course of the development and testing of the sensor the air–vapor mixtures of flammable liquids were prepared using the calibration chamber.

The procedure of preparation of the air–vapor mixtures in calibration chamber is based on the Mendeleev-Clapeyron equation (1):

$$pV = \frac{p_0 V_0}{273.15} \cdot (t + 273.15) \tag{1}$$

where p_0 – gas pressure at the temperature of 0 °C and gas volume V_0, mm Hg; *p* – gas pressure at the temperature *t* and gas volume *V*, mm *Hg*; *t* – ambient temperature, °C; V_0 – gas volume at the temperature of 0 °C and gas pressure p_0, dm^3; *V* – gas volume at the temperature *t* and gas pressure *p*, dm^3.

Since, in line with (1), 1 mol of gas at the ambient temperature of 273.15 °K and pressure of 101.325 kPa occupies the volume of 22.41 dm^3 using (1), the volume of liquid (V_l, µl) which ought to be evaporated in the enclosed volume to obtain the required component concentration in the air-vapor mixture can be determined as follows:

$$V_1 = 1000 \cdot \frac{Vc \cdot c + Vg \cdot c}{22.41} \cdot \frac{273.15}{273.15 + t} \cdot \frac{Pa - Pw}{760} \cdot \frac{M}{\rho} \cdot \frac{C}{100} \tag{2}$$

where *t* – ambient temperature, °C; *M* – molecular weight of the liquid, g/mol; *p* – liquid density, g/cm^3; V_{cc}, V_{gc} – volume of the calibration chamber and gas connections for connecting sensor to the calibration chamber, dm^3; P_a – atmospheric pressure, mm Hg; P_W – partial pressure of water vapor at the temperature *t*, mm Hg; *C* – concentration of vapor of flammable substance, volume fraction, %.

For flammable substances in (2), the value "lower explosive limit" (LEL) is usually applied for calculating the liquid volume V_l to obtain the required pre-explosive concentration expressed as LEL percentage (% LEL).

The sensor's sensitivity to the measured component was evaluated through evaporation of the liquid substance in the calibration chamber.

It should be taken into account that, when performing the measurements, the substance put into the calibration chamber must completely come into the gas–vapor phase. During the analysis of the sensor sensitivity to petrochemical products that contain heavy hydrocarbons (diesel fuel, kerosene, etc.), for instance, the amount of the substance cannot be evaporated completely. In this case, when determining sensitivity to the measured component, the sensor's output signal must be correlated with the amount of

Table 1
List of some of flammable substances monitored by the developed sensor.

Component name	LEL (vol%)	Component name	LEL (vol%)	Component name	LEL (vol%)	Component name	LEL (vol%)
Methane	4.4	Ethanol	3.1	Ethylene	2.3	Hexane	1.0
Ethane	2.5	Octane	0.8	Natural gas	5.0	Propanol	2.1
Propane	1.7	Acetone	2.5	Liquefied gas	1.5	Kerosene КТ-1	0.7
n-Butane	1.4	Benzol	1.2	Methanol	5.5	Butanol	2.6
i-Butane	1.3	Toluol	1.1	Diesel fuel (summer, winter)	0.5	Fuel for rocket engines	1.5
Pentane	1.4	Benzine	1	Oil “Urals”	1.2	White spirit	1.4

the evaporated substance. For that purpose it is necessary to weigh the evaporator of the calibration chamber with the known weight before and after the analysis.

Data on the output characteristics and correction coefficients for the measured components obtained using the calibration chamber, or in the case of monitoring concentrations of gaseous components SSS-TGM, are saved in the nonvolatile memory of the sensor. After that, the type of the measured component for monitoring its pre-explosive concentrations is selected by the user with the help of the service software installed on PC.

4.2. Results

Eventually our approach allows the end user to avoid the labor-intensive activity of the sensor adjustment considering the measured components under the actual operating conditions, and provides the user with the complete and accurate information on the resultant pre-explosive concentrations of flammable gases and vapors of flammable liquids.

Fig. 4 shows the absorption spectrum of some hydrocarbons which can be detected by the sensor: methane, ethane, propane, butane, pentane, hexane. The absorption spectrum have been obtained using FT-IR Spectrometer Varian 640-IR. The absorption region of these hydrocarbons lies in the wavelength range of 3.2–3.5 μm. In this range, the most intensive absorption is on the wavelength 3.4 μm. The detailed analysis of the obtained absorption characteristics and characteristics of other hydrocarbons is presented in [12,13]. This analysis helps to define the operating wavelength at which the detection of components concentration must be carried out. In the proposed sensor the monitoring of substances concentrations is carried out at the wavelength 3.4 μm. The list of flammable substances monitored by the developed sensor is given in Table 1.

Fig. 5 shows the output characteristic of the sensor in the presence of test gas mixtures (TGM) CH_4–N_2 in the following order: N_2 (zero gas) – TGM No. 2 (52.2% LEL) – TGM No. 1 (96.1% LEL) – TGM No. 2 (52.2% LEL) – N_2 (zero gas) – TGM No. 1 (96.1% LEL) – N_2 (zero gas) – TGM No. 3 (23.4% LEL). This testing sequence is determined by the state standard GOST 13320-81 [28]. The duration of each gas supply is 4 min. We first evaluate how the sensor node reacts on the zero gas which corresponds to the origin of the measurement scale. We then supply gases which correspond to the center and end of the scale. The second supply of the gas corresponding to the center of the scale helps us to evaluate variation between two similar measurements. As we see from Fig. 5 there is no significant variation. After supply of zero gas we evaluate the end of the scale. Finally, TGS No. 3 enables us to evaluate the scale linearity in full range.

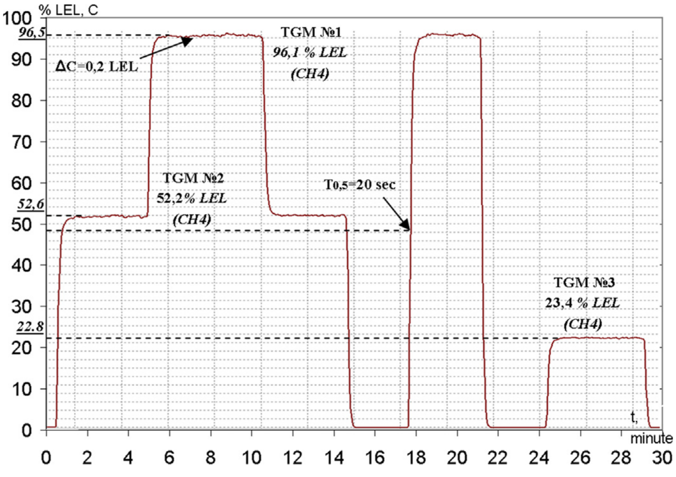

Fig. 5. Output characteristic of the sensor tested with gas mixtures CH_4–N_2.

The obtained results demonstrate that the basic characteristics of the developed sensor are: the measuring range (0–100% LEL), setting time at T 0.5 level (20 s), limits of intrinsic error ($\leq\pm(2.5+0.05\cdot C_{in})$% LEL), variations in steady state ΔC (0.2% LEL), permissible error at the end of the scale (±7.3% LEL; the diagram actually demonstrates 0.4% LEL; this error in other gas supply tests does not exceed 0.6% LEL). The sensor complies with the requirements of long-term stability according to the state standard GOST R 52350.29.1–2010 [29]. The operating time without readings adjustment is 12 months. The minimum service lifetime of the sensor is five years.

5. Conclusion

In this work we have demonstrated the optical absorption infrared sensor for detecting LEL of flammable gases and vapors of flammable liquids. The sensor node is of compact design which allows the user to deploy it in a difficult to access area. Besides, it can be easily interfaced with the external devices and integrated in the existing gas leak monitoring systems. The sensor is able to monitor up to 30 components and can be used as a part of gas analyzers for air monitoring within, both indoor and outdoor, in chemical, petrochemical and oil processing industries where the risk of leak of explosive substances is high. As for the outdoor applications, the sensor node is equipped with a heating system for the electronic components sensitive to low temperature. The sensor can also be applied as a part of the atmosphere control systems at hazardous industrial facilities.

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Biographies

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