

Estimation of a Gas Mixture Explosion Risk by Measuring the Oxidation Heat Within a Catalytic Sensor

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Abstract—Combustible gas mixtures and flammable vapors are present in the operating environments of many industries. Detection of the presence of these combustible gases and vapors and assessment of the explosion hazard is of vital importance to ensure that mitigation of the potential hazard can occur before an explosive concentration is reached. In this work, we introduce a gas mixture explosion risk estimation technique for a catalytic sensor. The contribution of this work is threefold. First, we propose the idea of explosion estimation of unknown gas mixtures, which are based on the measurement of heat dissipated during the mixture oxidation at a slow rate. Second, the analysis of transient oxidation processes and sensor response is performed for devising the associated computational scheme to be implemented in a low-power microcontroller. Third, we implement the proposed computational scheme in a wireless sensor node and carry out experiments with various gas mixtures for demonstrating the feasibility of our approach. Combustible heat of gas mixtures of methane, propane, butane, and hydrogen were studied at various concentrations in the range of 28%–56% lower explosive limit. The measurement procedure takes 8.5 s.

Index Terms—Explosions, gas detectors, gas industry, hydrocarbon detection, leak detection.

I. INTRODUCTION

COMBUSTIBLE gases are part of many industrial processes and a number of industries manage the use of them either directly as part of a controlled process or indirectly within an operating environment. Undetected leaks and inadvertent release may lead to hazardous consequences involving accidents, financial losses, and fatalities. Overheating engines and sparks from commutators in oil rigs, for example, is one of many potential sources that could ignite these gases, cause fire, explosion,

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expensive damage and fatalities (\$US 515 000 000 loss, Petrobras P36 rig in Brazil—gas explosion, 11 fatalities in 2001 [1]). In most cases, hydrocarbon combustible gases appear in the environment in gas mixtures. The major problem is being able to quickly assess the explosion risks of this mixture and take immediate measures against the leakage. However, assessment of an explosion hazard of a combustible gas mixture is not a trivial task as the composition and concentration of single gas molecules within the gas mixtures not known precisely. Moreover, lower explosive limits (LEL) of each single gas molecule in the mixture may vary considerably (see Table I) making the assessment even harder.

Currently, there are two widely used technologies for detecting a combustible gas leak within an industrial facility: infrared (IR) absorption spectroscopy [2] and catalytic method [3]. Both approaches have their strengths and weaknesses, but in terms of combustible gases, IR detectors do not allow us for hydrogen detection since the molecules that do not have a dipole moment cannot absorb the IR emission [4].

Although catalytic and IR detectors are typically limited to detecting a single combustible gas, a few works report on successful detection of gas mixtures or multiple gases [5], [6], though being power consuming options. Currently, the assessment of gas mixtures is carried out by recognition of each single gas in the mixture [6], determination of their concentrations, calculation of the mixture LEL, and its comparison with the theoretical thresholds. This approach requires complex measurement facilities and measurement procedures, i.e., involving multiple sensors. In fact, the mixtures propensity to explode can be detected without recognising the gases in the mixture.

In the forthcoming era of Internet of Things (IoT), it is expected that the IoT devices, i.e., “things,” will be deployed everywhere, including the difficult-to-access industrial areas, and can be accessed anytime from anywhere [7]. In the scope of IoT, a wireless sensor network (WSN) paradigm is a pillar technology for enabling autonomous monitoring applications where tiny sensing devices measure physical phenomena, preprocess the data, and send this data to the user over a wireless network. Indeed, the WSN concept introduces a number of advantages for the IoT devices: they do not need expensive cabling production, they are independent on a power grid, and are easier in terms of deployment and debugging [8]. However, shifting towards the IoT implies strict requirements for smart sensing: the sensors are to be reused in various applications and contexts (the

TABLE I
WIDELY USED HYDROCARBONS IN THE OIL AND GAS INDUSTRY

N ^o *	Flammable Gas	Concentration C_{LEL} , %vol., RU [17]/ US+EU [18]**	Standard Combustion Heat Q^0 , kcal/mole	$C_{LEL} Q^0$, kcal/mole, RU/US+EU
1	Methane CM_4	4.4/5.0	191.554	8.428/9.77
	Ethane C_2H_6	2.5/3.0	344.3	9.411/10.34
	Propane C_3H_8	1.7/2.1	498.6	8.49/10.47
	Butane C_4H_{10}	1.4/1.6	661.1	9.25/10.57
	n-pentane C_5H_{12}	1.4/1.5	838.04	11.73/12.57
	n-hexane C_6M_{14}	1.0/1.1	926.5	9.264/10.19
	n-heptane C_7M_{16}	1.1/1.05	1073.02	10.70/11.27
2	Octane C_8H_{18}	0.8/ n/a	1219.53	9.776/ n/a
	Benzol C_6H_6	1.2/1.3	832.88	9.99/10.82
	Toluol C_7H_8	1.1/1.2	899.86	9.90/10.79
3	Styrol C_8H_8	1.0/1.1	1060.19	10.602/11.66
	Methanol CH_3OM	5.5/6.7	182.43	10.034/12.22
	Ethanol C_2H_5OM	3.1/3.3	336.295	10.425/11.09
	Isopropyl alcohol C_3H_6OH	2.2/2.2	489.968	10.779
4	Ethylene C_2H_4	2.7/2.7	314.799	8.48
	Propylene C_3H_6	2.0/2.4	458.345	9.16/11.00
	Butane C_4H_8	1.6/1.6	607.29	9.71
5	Acetaldehyde CM_3-CMO	4.0/ n/a	259.599	10.384/ n/a
	Acetone $CM_3-CO-CM_3$	2.5/2.6	435.029	10.876/11.31
	Methyl ether CH_3OCH_3	2.7/3.4	315.754	8.525/10.73
6	Diethyl ether $(C_2H_5)_2O$	1.7/ n/a	604.519	10.277/ n/a
	Acetylene C_2H_2	2.5/2.5	310.739	7.77
	Propyne C_3H_4	1.7/1.7	442.2	7.52
7	Cyclopropane C_3H_6	2.4/2.4	499.1	11.98
	Cyclobutane C_4M_8	1.84/ n/a	608.03	11.19/ n/a
	Cyclohexane C_6H_{12}	1.2/1.3	881.103	10.573/11.45
	Hydrogen M_2	4.0/4.0	57.79	2.31

* – the first column shows homologous series: ‘1’ is the methane family, ‘2’ is the benzol family, ‘3’ is the monobasic alcohol, ‘4’ is the alkene family, ‘5’ is the aldehydes and ketones, ‘6’ is the ethers, ‘7’ is the alkenes, ‘8’ is the cycloalkanes.

** – numbers in this column vary due to different measurement setup and measurement procedures across standards [17], [18].

so-called proximity service), pieces of software have to substitute expensive, nonreliable, and heterogeneous hardware [9].

This work introduces a design for the analysis of the total explosiveness of gas mixtures in the atmosphere when the mixture components are unknown. The primary novel aspect is a measurement method for heat emitted during the gas mixture combustion in the sensor reaction chamber of a known volume. The amount of measured heat is associated with dangerous gas mixture concentrations that could pose a combustion hazard. The method is proposed for catalytic sensors and can be implemented in a typical microcontroller unit (MCU) for low-power embedded sensing devices.

For demonstrating the feasibility of our approach, we developed a wireless sensor node for gas mixture assessment and carried out the experiments with gas mixtures. In this work, we used a single catalytic sensor, compared to the state-of-the-art solutions relying on multiple sensors [6], and proposed a sensing circuit with a newly designed heating profile. The proposed technique is highly relevant for the IoT paradigm as it enables the reuse of a single catalytic sensor for numerous gas detection applications.

Key features of this work are: 1) assessment of explosiveness of *unknown* gas mixtures, 2) sensing *both* single gases and gas mixtures, and 3) only *one catalytic sensor* is required for sensing gas mixtures.

This paper is organized as follows: Section II will overview the state-of-the-art gas sensing approaches and their application in IoT. Also, it introduces the underlying concepts and relevant works for gas mixture detection. Section III presents the proposed approach for the assessment of gas mixture explosiveness. In particular, it describes the sensing circuit and measurement procedure followed by the analysis of transient oxidation process and sensor response. The experimental testbed is presented in Section IV where we mainly focus on the gas measurement setup. Experimental results are shown in Section V. These results demonstrate the high potential and effectiveness of the proposed technique for industrial IoT applications. Finally, we provide concluding remarks in Section VI.

II. GAS SENSING

In this section, we describe some typical approaches for gas sensing, discuss some smart gas sensing techniques and finally present some relevant research works for gas mixture detection.

A. Approaches

As mentioned earlier, IR absorption [2] and catalytic beads [3] are widely used for detecting a single combustible gas in the area monitoring applications. However, the IR detectors do not allow us for hydrogen detection, which may prevent their application for gas mixture sensing. Recent works on the sensor nodes based on a catalytic sensor report reasonable power consumption levels [3]. Catalytic sensors are good as leak detectors, but suffer from continuous flammable vapors in the environment and they are subject to poisoning in the presence of high concentrations of flammable gases. Recent advances in low-power and portable sensing devices include film (colorimetric) gas sensors [10], quartz resonators [11], resonant microcantilevers [12], and printed meandered electrodes [13], which are characterized by a long response time (up to several minutes) and, therefore, fail to meet safety requirements.

In terms of IoT, context-aware gas sensing is realized through sensing the presence of people in the environment and consequent adjustment of the gas sensing duty cycle [14] or through applying cognitive technologies for learning the context and switching between different sensing technologies [15]. Sensor fusion techniques perform preprocessing of collected data and allow for the inference procedures based on the concentration of chemical species in the atmosphere [16].

B. Gas Mixture Detection

IR detectors are typically calibrated and used for detecting a single combustible gas by measuring the energy absorbed by the particular gas for a given wavelength. Nonetheless, a set of photoacoustic spectroscopy and Nondispersive Infrared absorption can be used for sensing multiple gases [5].

The operating principle of catalytic sensors is based on changing its resistance in normal conditions R_{T_0} to R_T when the sensing element with the temperature coefficient of resistivity β is heated up for ΔT K during the measurement procedure. The sensor resistance R_T is a function of temperature and is

$$R_T = R_{T_0} \cdot (1 + \beta \cdot \Delta T). \quad (1)$$

To the best of our knowledge, multiple catalytic gas sensors are used for detecting gas mixtures [6]. There is a lack of research and experimental efforts for detecting gas mixtures relying on a single catalytic sensor. This research is highly important for the IoT applications as catalytic sensors meet safety requirements and demonstrate high performance in terms of power consumption and sensor response time [3].

III. APPROACH

Table I presents known values of standard combustion heat Q^0 emitting during the combustion of different hydrocarbons. These values vary greatly. However, multiplying Q^0 by %LEL C_{LEL} provides the resultant value $C_{LEL} \cdot Q^0$ which is comparable for most gases (see **Table I**). Thus, the explosiveness of the atmosphere can be estimated using this effect. In this case, Q^0 is the constant for each particular hydrocarbon. At the same time, C_{LEL} is the subjective constant since it depends on the measurement conditions, as well as the safety standards. That is why C_{LEL} constant may differ between countries.

The cornerstone of the proposed approach is the phenomena of Q^0 multiplied by C_{LEL} . The resultant value $C_{LEL} \cdot Q^0$ helps in assessing at what extent the concentration of hydrocarbon gas mixture is dangerously explosive. **Table I** shows dangerous explosive values of $C_{LEL} \cdot Q^0$. Since the integral parameter $C_{LEL} \cdot Q^0$ varies for different hydrocarbons (see **Table I**) the approach provides only a coarse estimation of volatility. For calculating $C_{LEL} \cdot Q^0$, it is important to measure the sensor response during the oxidation reaction in the sensor reaction chamber. We measure the sum of the sensor responses over the time until the reaction stops. For successful realization of this task it is vital to limit the gas diffusion to the sensor reaction chamber. This limitation guarantees the analysis of a fixed volume of gas. To do this, we used a catalytic sensor with a small hole diaphragm in a sealed cap. The diaphragm helps to control the speed of gas flow into the chamber. We defined the diaphragm diameter empirically. The speed of flow must be much lower than the speed of gas oxidation in the package. At the same time, the speed of chamber delivery must be less than the sensor response time to gas detect in the environment [19].

For detecting % LEL of combustible gases we measure the sensor voltage response from the sensing circuit presented in Section III-A. The response signal corresponds to the amount of heat dissipated during the gas oxidation process within the

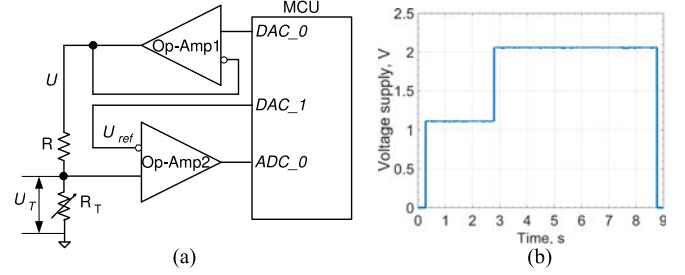


Fig. 1. (a) Sensing circuit. (b) Sensor heating profile.

sensor. We performed the analysis of transient oxidation process and sensor response in Section III-B.

A. Measurement Procedure

The designed wireless sensor node prototype includes four units: processing, sensing, wireless communication, and power conditioning. The *processing unit* is built around the ADuC831 MCU due to its low power consumption, 12-bit analog to digital converter (ADC) and digital to analog converter (DAC). The data acquisition is realized at 50 kilosamples per second. The ADC resolution is 0.055 mV. As for the reference voltage, we use the ADC nominal internal reference voltage 2.5 V. This allows us to be as precise as possible, in this case, for generating the sensor heating profile, calculating the sensor response and making intermediate calculations.

The *sensing circuit* is based on a catalytic sensor DTK-3 manufactured by NTC-IGD, Russia. It is fabricated on nano-porous gamma anodic alumina membrane with a thickness $30 \mu\text{m}$ using planar technology. Microheaters for the sensing layer are fabricated by magnetron sputtering of a platinum target and covered by a thin film layer of Al_2O_3 to prevent its degradation. Microheater is a meander and is about $200 \times 200 \mu\text{m}^2$ [20]. Catalytic sensors are typically used in the range of the LEL gas concentration for the purpose of high sensitivity, linear and fast response, reasonably low power consumption, and cost. The working principle of a catalytic sensor consists in measuring the change in its conductivity during the exposure to the flameless oxidation of a combustible gas, i.e., oxidation reaction, on the catalytically active area.

The *wireless communication* is realized using the low power ETRX3 wireless transceiver. It supports IEEE802.15.4 standard and operates in the license exempted 2.4 GHz ISM band. The transceiver is equipped with an integrated on-chip antenna with a transmission range of approximately 25 m.

The *power conditioning* unit provides a stable 2.7 V supply for the wireless sensor node and consists of 3 V, 1000 mAh Li battery, and TPS61200 DC/DC converter.

For taking a measurement the sensor R_T is embedded in a voltage divider circuit [3] with resistor R (10Ω in our case) shown in Fig. 1(a). The sensing circuit is controlled by the ADuC831 MCU which generates a specific heating profile [see Fig. 1(b)] for the sensor. The profile includes two heating pulses: the first one is for hydrogen and the second for hydrocarbons combustion. This is why this approach will work for both

pure H_2 and hydrocarbon- H_2 mixtures. The first pulse is at 1.1 V, the second pulse is at 2.1 V, and techniques such as low-pass/bandpass filtering are not required. The profile, i.e., supply voltage U , is generated by the software running on the MCU and supplied to the sensor via the integrated DAC. *Op-Amp1* operational amplifier ensures sufficient heating current which is otherwise not available at the MCU. The measured response U_T from the sensing circuit is supplied to the ADC integrated in the MCU via the *OpAmp2*. It serves by amplifying the measured signal and excluding the constant component from it by relying on the reference voltage U_{ref} generated by DAC. Nulling is compensated at DAC0 and drift is compensated during the sensor calibration. One measurement takes 8.5 s [see Fig. 1(b)]. The next measurement is taken when there is enough gas in the chamber. It takes about 10 s for fulfilling the chamber. We take the measurements every 20 s.

Concentration of flammable gas C_{fl} in the environment can be detected as follows: we place the sensor in the atmosphere with clear air and measure the amount of heat Q° emitted during the measurement procedure. The sensor is heated up by the pulse shown in Fig. 1(b). Next, we carry out the same experiment, but in the presence of a combustible gas with known C_{LEL} in the environment and measure the amount of heat Q emitted in the same time interval,

$$C_{fl} = (Q - Q^\circ)/(C_{LEL} \cdot q_0) \quad (2)$$

where q_0 is a standard enthalpy of reaction, kJ/mol.

For measuring the amount of heat Q_{ox} emitted during the gas combustion on the sensor we measure the sensor response U_{T1} in the presence of gas in the environment and U_{T0} without it. The measurement of sensor response is carried out until it stops changing over time. The sensor output voltage depends on the catalytic sensor resistance and, therefore, its temperature as it is given by (1).

For taking these measurements and calculating the concentration of flammable gases in the atmosphere we focus on the analysis of transient oxidation process and sensor response in the next section.

B. Transient Oxidation Process and Sensor Response

Prior to starting the analysis of the transient oxidation process and sensor response we make the following assumptions.

- 1) The measurement chamber is completely closed during the gas measurement process and is completely open between the measurements.
- 2) Concentration of the flammable gases in the chamber and in the outside environment is identical in the beginning of the measurement process.
- 3) Electrical characteristics are constant values at the operation temperature.
- 4) Ambient temperature and heat transfer coefficient are constant values.

The sensor resistance R_T is a function of the sensor temperature and can be estimated by (1) β , for platinum (Pt) in our case is $0.0033 \text{ } ^\circ\text{C}^{-1}$.

According to the sensing circuit used in this work [see Fig. 1(a)] the resistance R_T can be calculated as follows:

$$R_T = \frac{U_T \times R}{U - U_T} \quad (3)$$

Using (1) and (3), we can calculate the sensing element temperature T as the function of U_T

$$T = T_0 - \frac{1}{\beta} + \frac{U_T \cdot R}{R_{T0} \cdot \beta \cdot (U - U_T)} \quad (4)$$

where U is the heating (supply) voltage set by the DAC of the MCU and Op-Amp1 [see Fig. 1(a)] and is a known value.

If there would be no thermal exchange with the environment the heat generated during the measurement procedure can be calculated as:

$$\Delta Q = cm\Delta T \quad (5)$$

where c is the sensing element specific heat, $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, m is the mass of sensing element, kg.

The total amount of heat on the sensor is defined as the sum of power of all thermal processes over time

$$\Delta Q = P\Delta t. \quad (6)$$

The heating power P is composed of power generated by the electric heat, P_e , and combustible gases oxidation heat, P_{ox} , allowing us for some amount of dissipated heat, P_d (all in W):

$$P = P_e + P_{ox} - P_d \quad (7)$$

where P_e is generated by the current I flowing via the sensor R_T and is given by the following:

$$P_e = I^2 \cdot R_T = \frac{(U - U_T)^2}{R^2} \cdot \frac{U_T \cdot R}{U - U_T} = \frac{U_T \cdot (U - U_T)}{R} \quad (8)$$

Dissipation heat P_d is calculated by

$$P_d = \alpha \cdot F \cdot (T - T_a) \quad (9)$$

where α – is the heat transfer coefficient, $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, F is the heat transfer area, m^2 , T is the temperature of sensing element, K, T_a is the ambient temperature, K.

The heat dissipation is due to convection, thermal conductivity of gas medium, thermal radiation of the carrier, and current leads.

In the presence of combustible gases in the environment the oxidation reaction starts and generates extra oxidation heat power P_{ox}

$$P_{ox} = Q_{M0} \cdot \gamma_e \cdot C_g \quad (10)$$

where Q_{M0} is the lowest enthalpy of formation, J/m^3 , γ_e is the effective diffusion conductivity of sensing element, m^3/s , defined in the technical specification of the sensing element and depends on the temperature, C_g is the flammable gas concentration, % v.v.

Using (8)–(10) and equating right-hand sides of (5) and (6) we can rewrite (7) and proceed to differential form:

$$dT = \frac{1}{c \cdot m} \left(\frac{U_T \cdot (U - U_T)}{R} + Q_{M0} \cdot \gamma_e \cdot C_g - \alpha \cdot S \cdot (T - T_a) \right) \cdot dt. \quad (11)$$

Equation (11) describes the heating process of sensing element.

Let us consider the total amount of heat Q_0 generated in clean air environment and heat Q_1 generated in the presence of combustible gases:

$$dQ_0 = cm dT_0 = \left(\frac{U_T \cdot (U - U_T)}{R} - \alpha \cdot S \cdot (T - T_a) \right) \cdot dt \quad (12)$$

$$dQ_1 = cm dT_1 = \left(\frac{U_T \cdot (U - U_T)}{R} + Q_{M0} \cdot \gamma_e \cdot C_g - \alpha \cdot S \cdot (T - T_a) \right) \cdot dt. \quad (13)$$

The heat generated by the oxidation reaction is the difference between dQ_0 and dQ_1 . It can be calculated by integrating this difference:

$$\begin{aligned} & cm (T_1(t) - T_0(t)) \\ &= \int_0^t \frac{U_{T1} \cdot (U - U_{T1}) - U_{T0} \cdot (U - U_{T0})}{R} dt \\ &+ Q_{ox} - \int_0^t \alpha \cdot S \cdot (T_1 - T_0) dt. \end{aligned} \quad (14)$$

Since the steady state temperature at $t \rightarrow \infty$ is equal for both the clean air environment and the environment with the presence of combustible gases, the left hand side of (12) is 0. It can be therefore written as

$$Q_{ox} = \int_0^t \alpha \cdot S \cdot (T_1 - T_0) dt - \int_0^t \frac{U_{T1} \cdot (U - U_{T1}) - U_{T0} \cdot (U - U_{T0})}{R} dt. \quad (15)$$

In the range of operation temperature, the sensor voltage U is continuously supplied to the sensor and is much higher than its output signal U_T . It means that $U - U_{T1} \approx U - U_{T0}$ where U_0 is the sensor response in clean air and U_1 is the response in the presence of gas. Consequently, the second term in (15) is much less than the first term, resulting in

$$Q_{ox} \approx \int_0^t \alpha \cdot S \cdot (T_1 - T_0) dt. \quad (16)$$

Using (4) we rewrite (16) as

$$Q_{ox} = \int_0^t \alpha \cdot S \cdot \left(\frac{U_{T1} \cdot R}{R_{T0} \cdot \beta \cdot (U - U_{T1})} - \frac{U_{T0} \cdot R}{R_{T0} \cdot \beta \cdot (U - U_{T0})} \right) dt. \quad (17)$$

Then, we put the constant outside the integral as follows:

$$Q_{ox} = \alpha \cdot S \cdot \frac{R}{R_{T0} \cdot \beta} \int_0^t \left(\frac{U_{T1}}{U - U_{T1}} - \frac{U_{T0}}{U - U_{T0}} \right) dt. \quad (18)$$

Direct calculation of heat is inconvenient, since we must take into consideration the sensor-specific parameters, e.g., mass of sensing element and effective surface area. We rewrite (2) for unknown C_{fl} and known C'_{fl} concentrations of flammable gas as $C_{fl} = (Q - Q^0)/(C_{LEL} \cdot q_0) = Q_{ox}/Q_{expl}$ and $C'_{fl} = Q'_{ox}/Q_{expl}$ where Q_{expl} is the value equal for known and unknown concentrations (see Section III). Knowing this we can calculate C_{fl} as follows:

$$C_{fl} = \frac{Q_{ox}}{Q_{ox'}} \cdot C'_{fl} \cdot 100\%. \quad (19)$$

Using (18) the concentration of the flammable gas C_{fl} in (19) can be calculated as

$$C_{fl} = \left(\int_0^t U_{T1} dt - \int_0^t U_{T0} dt \right) / \left(\int_0^t U'_{T1} dt - \int_0^t U_{T0} dt \right) \cdot C'_{fl} \cdot 100\%. \quad (20)$$

Modern ADCs have high sample-rate and are able to measure voltage with high resolution. We can thereby move from integral to sum operation,

$$C_{fl} = \frac{\sum(U_{T1} - U_{T0})}{\sum(U'_{T1} - U_{T0})} \cdot C'_{fl} \cdot 100\% = \frac{\sum U_{T1} - U_{T0}}{\sum U'_{T1} - U_{T0}} \cdot C'_{fl} \cdot 100\% \quad (21)$$

where U_{T1} is the sensor response in the presence of gas in the environment and U_{T0} without it, U'_{T1} is the sensor response in the presence of test gas. U_{T0} and U'_{T1} are defined during the sensor calibration.

Equation (21) can be used in embedded systems as simple and reliable instrument for measuring the explosiveness of the environment.

IV. TESTBED

For validation of the proposed approach presented in Section III, we fabricate a sensor node shown in Fig. 2 and the resultant system in the measurement setup which is shown in Fig. 3.

Wireless communication between the sensor node and personal computer (PC) is realized through the measurement chamber environment. The PC is equipped with the master wireless unit which automatically configures the wireless network and performs its self-diagnostics, as required.

Fig. 3 shows the testbed for making a gas mixture and its supply to a measurement chamber. First, we select single calibration gases for making a mixture. We use different mixing ratios for it. The test gases, their concentration and concentration in the mixture are shown in Tables II and III. Valves and rotameters control gas flow rate and measure this rate, respectively. The mixing valve creates the gas mixture, which then is supplied to the measurement chamber via a common valve and common rotameter which perform the same actions as valves and rotameters. The wireless sensor node is placed into the measurement

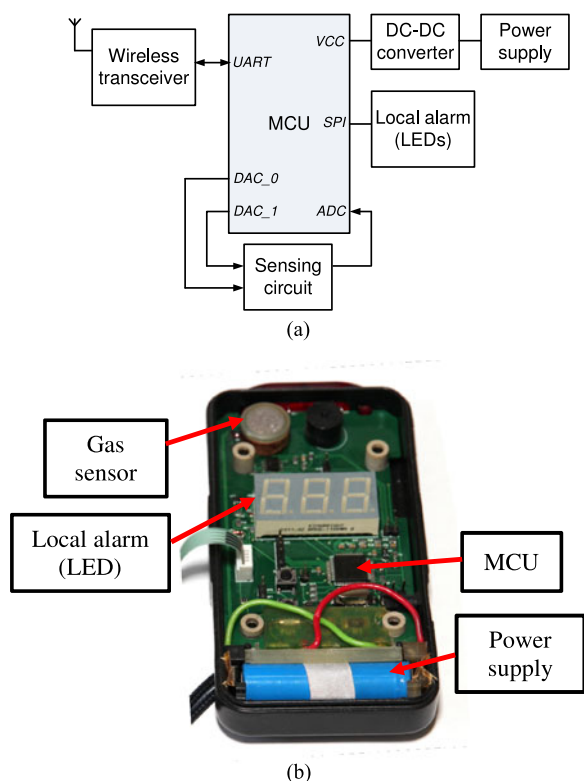


Fig. 2. Wireless sensor node. (a) Block diagram. (b) Prototype.

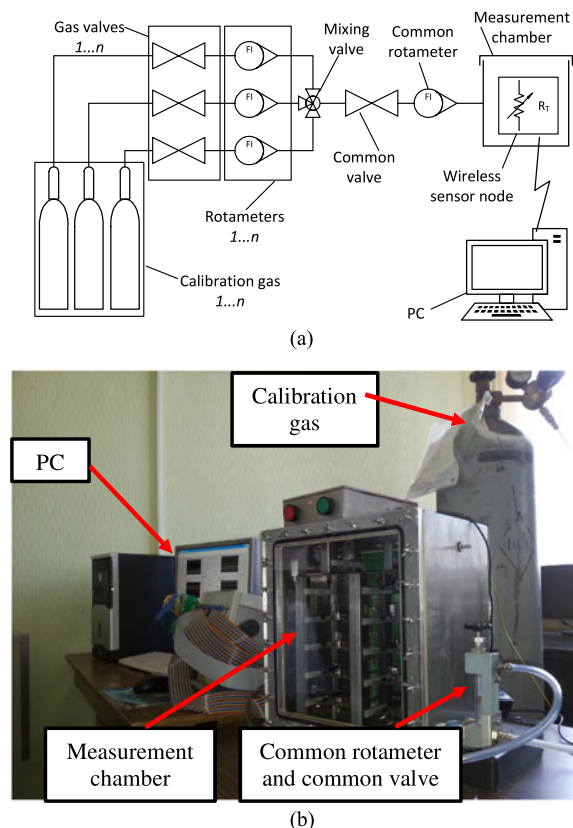


Fig. 3. Gas mixture sensing testbed.

chamber, takes measurements and communicates them to the PC over the wireless link.

To guarantee the proper mixture flow into the sensor reaction chamber, the hole diameter of the sensor sealed cap must be 0.3 mm. For detecting % LEL of combustible gases we measure the sensor voltage response from the sensing circuit and compare it with the reference voltage. The reference voltage levels are defined during the calibration process when a predefined gas concentration is supplied to the sensor and its response (reference value) is recorded in the MCU of the sensor node. Function for calculating % LEL is given by (21).

V. RESULTS

In this section we detail the experimental results of the design operational testing.

Table II shows the experimental results on estimation of explosiveness of eight gas mixtures. We have investigated different combinations of two-component mixtures of flammable gases in the air. As the initial mixtures, we used three calibration hydrocarbon gas mixtures (methane, propane, butane) and hydrogen, all with known concentrations. Experimental results are obtained using the proposed approach (see Section III), and in particular (21), implemented in the wireless sensor node (see Section IV). These results are compared against the theoretical values that are calculated using a well-known formula for a combustible gas mixture from an industrial standard [21]. Different single gas concentrations in the resultant mixture are obtained by controlling the gases' flows on the way to the measurement chamber as it is shown in Fig. 3. This is why initially equal single gas concentrations (column "Test gas concentration, %vol." in Table II) differ in the gas mixture (column "Test gas concentration in mixture, %vol." in Table II). These two columns show how close the detected mixture is to an explosive situation, i.e., 100%. We note here that single gases are in the air. In all experiments the mixture concentration is less than standard LEL meaning that there is no explosion risk from presented gas mixtures. Experimental results presented in Table II are in agreement with theoretical LEL values.

Results of a more complicated experiment where we estimate the explosiveness of gas mixture consisting of three gases are shown in Table III. Mixtures of different combinations of three-component gases are obtained in the same way as described above. The only difference is that we supplied three single mixtures to the measurement chamber and controlled gas flow rate of each gas. In total we evaluated four mixtures and the experimental results are in line with the theoretical values.

Alternative ways for flammable mixtures analysis are typically grounded on a number of mathematical approaches [22], [23] or associated with the application of multi wavelength IR sensor [24]. In [22], the flammability of a process gas stream is modelled using Le Chatelier's principle. However, this approach helps perform the analysis of mixture flammability by detecting the mixture components followed by the analysis of their cumulative effect. Video camera and image processing techniques can be applied for detecting gas mixtures [23]. Makeenkov *et al.*

TABLE II
ESTIMATION OF EXPLOSIVENESS OF TWO-COMPONENT MIXTURES

	Test Gas Concentration, %vol.		Test Gas Concentration in Mixture, %vol.		Theoretical LEL, %vol.	Mixture Concentration, %vol.	Theoretical LEL, %LEL	Experimental LEL, %LEL
	Gas 1	Gas 2	Gas 1	Gas 2				
1.	1.47 CH ₄	1.01 C ₃ H ₈	1.17	0.20	3.569	1.378	39	39
2.	1.47 CH ₄	1.01 C ₃ H ₈	0.29	0.80	2.033	1.102	54	56
3.	0.96 H ₂	1.01 C ₃ H ₈	0.67	0.30	2.816	0.975	35	36
4.	0.96 H ₂	1.01 C ₃ H ₈	0.17	0.54	1.662	0.719	43	47
5.	0.96 H ₂	0.665 C ₄ H ₁₀	0.49	0.32	2.321	0.819	35	38
6.	0.96 H ₂	0.665 C ₄ H ₁₀	0.85	0.12	3.435	0.966	28	30
7.	1.47 CH ₄	0.665 C ₄ H ₁₀	1.18	0.13	3.641	1.315	36	38
8.	1.47 CH ₄	0.665 C ₄ H ₁₀	0.98	0.22	3.153	1.202	38	40

TABLE III
ESTIMATION OF EXPLOSIVENESS OF THREE-COMPONENT MIXTURES

	Test Gas Concentration, %vol.			Test Gas concentration in Mixture, %vol.			Theoretical LEL, %vol.	Mixture Concentration, %vol.	Theoretical LEL, %LEL	Experimental LEL, %LEL
	Gas 1	Gas 2	Gas 3	Gas 1	Gas 2	Gas 3				
1.	0.96 H ₂	1.01 C ₃ H ₈	0.665 C ₄ H ₁₀	0.59	0.14	0.16	2.588	0.897	35	37
2.	0.96 H ₂	1.01 C ₃ H ₈	0.665 C ₄ H ₁₀	0.69	0.05	0.15	2.863	0.894	31	33
3.	0.96 H ₂	1.01 C ₃ H ₈	0.665 C ₄ H ₁₀	0.07	0.07	0.56	1.526	0.712	47	50
4.	0.96 H ₂	1.01 C ₃ H ₈	0.665 C ₄ H ₁₀	0.65	0.16	0.10	2.767	0.921	33	35

[24], applied the optical absorption IR sensor for detecting up to 30 components in the environment, but this sensing system is capable of detecting single gas components in the air. Gant *et al.* empirically study the flammability of hydrocarbon and carbon dioxide (CO₂) mixtures [25]. The goal is to figure out how CO₂ affects fires and explosions caused by hydrocarbon releases.

VI. CONCLUSION

In this paper, we have presented a new approach for estimating the explosiveness of combustible gas mixtures using a catalytic sensor. The key feature of this design is the phenomena of combustion gas heat multiplied by %LEL which is rather equal for most gases. A low power MCU is required for realizing the proposed idea in practice. Moreover, the proposed approach results in a reduction of sensors on a gas mixture sensing platform and, therefore, reduction of its power consumption. Our experimental results demonstrate their agreement with theoretical values. This achievement is highly important for autonomous IoT and WSN monitoring solutions for many industrial processes and applications associated with area monitoring in terms of *unknown* combustible gas leaks. It is important to emphasize that our generic solution can be used for sensing single gases as well as gas mixtures.

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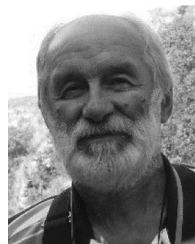
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