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Fast measurements of the methane concentration in coal mines with the use of dynamic error correction based on prediction

Abstract. *The primary reason for measuring methane is to improve the safety of the mines. The rapid detection of methane is very important from the point of view of safety of mine workers. This paper presents a concept of fast methane detection by prediction its concentration in dynamic states. Two methods of dynamic corrections of methane concentration - single-channel and double-channels were described. Then, the results of research and comparison of the two methods were presented.*

Streszczenie*. Jednym z głównych zagrożeń w kopalniach węgla kamiennego jest obecność metanu. W celu zapewnienia bezpieczeństwa pracy stężenie metanu musi być ciągle kontrolowane z uwagi na możliwość jego gwałtownych i nagłych zmian. Warunki występujące w miejscu pomiaru wpływają niekorzystnie na dynamikę czujnika (jego osłona ulega silnemu zabrudzeniu co znacznie pogarsza współczynnik jej dyfuzji)a. W artykule przedstawiono proponowaną metodę przyspieszenia uzyskania wyniku pomiaru stężenia metanu w warunkach występujących w kopalniach.* ***(Szybkie pomiary stężenia metanu w kopalniach węgla kamiennego z korekcją błędu dynamicznego na zasadzie predykcji).***

Keywords: dynamic error correction, methane sensor, pellistor sensor, safety in mines.
Słowa kluczowe: korekcja błędu dynamicznego, czujnik metanu, czujnik pelistorowy, bezpieczeństwo pracy w kopalniach.

Introduction

The coal mine methane is a term given to the methane gas produced or emitted in association with coal mining activities either from the coal seam itself or from other gassy formations underground. In range between 5% and 15%, known as the explosive range, methane can be ignited easily with the presence of an ignition source to create a violent methane explosion that may propagate in the presence of combustible coal dust [1, 2]. Coal mine methane has always been considered as a danger for underground coal mining as it can create a serious threat to mining safety and productivity due to its explosion risk [3].

One of the most important duties of ventilation in underground coal mines is to keep methane levels well below the explosive limit by diluting methane emissions that occur during mining. From these reasons the methane concentration should be controlled by continuous measurements [1, 2, 4].

Methane sensors use different detection technologies according to the three gas categories and these are pellistors, electrochemical, and infrared devices [1, 4, 5]. Typically pellistors are used for detecting methane and any flammable gas [2, 6, 7]. One of the disadvantages of pellistor sensor is a long response time [8, 9, 10]. This defect can be significantly reduced by using a dynamic correction method [11–13]. Such a method was shown in [14–16]. Article shows a way for use the correction method for pellistor sensors in coal mines for reducing the time to detect methane.

Dynamic error of methane sensor

Pellistors are gas sensors that detect combustible gases and vapours in air (or atmospheres containing oxygen), in concentrations approaching the explosive range. In this case, they are operating in a catalytic mode where the target gas is burnt and the heat liberated is measured by the sensor. The working principle of catalytic sensors is based on flammable gas oxidation: when a combustible gas comes in contact with the catalyst surface it is oxidised. The reaction releases heat, which causes the resistance of the wire to change [5–8].

A catalytic palletised resistor (or "Pellistor") consists of a very fine coil of platinum wire, embedded within a ceramic pellet. The signal produced by measurement setup is proportional to the gas concentration up to the lower explosive limit, or LEL [7]. The sensor will detect all combustible gases and vapours, although the response to higher hydrocarbons may not be high [17].

The thermal conductivity sensor comprises two beads, one of which is exposed to the target gas (the Detector) and the other sealed inside a chamber containing air (the Compensator). When the detector bead is exposed to a gas whose thermal conductivity is significantly different to that of air, the rate of heat loss from the bead will change, as will its resistance. This change measured is compared with the compensator bead [6].

Essential to the operation of methanemeter system are their dynamic properties, characterized mainly by the response time of the system to change the measured parameters, including to increase the methane content above the limit value. One of the basic ways to evaluate the dynamic properties of the measuring sensor is to determine the parameters of the response to a step change in the input (Fig. 1) [10].

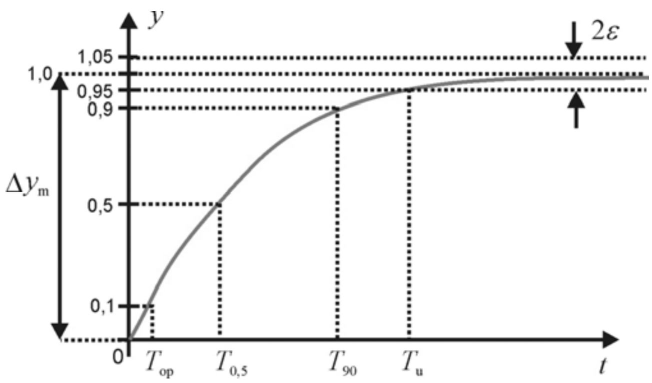

Fig.1. Some parameters that characterize the step response sensor

The dynamic properties of methanometers depend both on the dynamics of methane penetration by a cover flameproof, and the characteristics of the sensor itself, but the overall dynamic error is mainly due to the properties of the shield. From the point of view of consumable characteristics of the system for measuring methane important parameter measuring sensor is the T_{90} time delay defined as the time to reach the sensor output signal 90% of the set. A T_{90} time response to methane detection is usually provided in 5 - 10 seconds [1, 10, 15, 17]; a slight increase occurs when the sensor is protected by a sintered filter [4, 17].

Because of catalytic combustion the pellistor sensor must be placed behind a flameproof enclosure [1, 5, 7]. It normally contains a sintered metal flame arrester that also acts as a primary diffusion barrier through which the gas must pass before reaching the sensing element [7, 18, 19]. This factor cause the much longer time to receive the stable value of a methane concentration in the case of its rapid growth [20, 21].

Hindered the penetration of gas through the casing on an unforced diffusion is the cause of a large dynamic error (defined as a temporary difference methane concentration outside the measuring head and the inside of her), whose value, in the initial phase after step change, can reach 100%. This problem is especially evident in situations where the change in concentration occur in time, e.g. by ejection methane [10, 22].

Single channel dynamic correction

Dynamic errors are primarily caused by system delays. In this case dynamic error is caused by delay introducing by flameproof arrester. This delay can be variable because the shield is placed in dusty and polluted places in mine. Changes of time constant may be large what illustrates the figure 2.

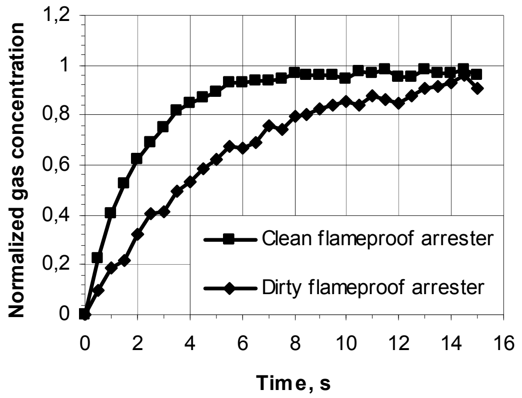

Fig.2. Changes of pellistor sensor time constant

Determination of a dynamic correction algorithm of a real measuring sensor requires knowledge of its dynamics especially measurement system time constant needed for formulation of differential equations. Therefore, correction algorithms must always be determined for specific measuring transducers and measurement systems, and the resultant equations must only be applied to the particular sensors [14, 15].

Dynamic properties of methane sensor can be modeled by a linear differential equation of n-th order, but usually transducer can be described by first order equation. This expression describes the dynamic processing error. When measured quantity changes occurs respectively slow, the parts of expression containing derivatives take values close to zero and this equation takes the form of the equation of ideal processing. Sensor output can be represented as the sum of the input quantity and dynamic error. This relationship allows us to determine the dynamic error at the output of the transducer to any changes of known input quantity [14, 15].

Dynamic correction is usually realized by microcontroller due to its numerical complexity. We assume that the measured value is converted to other quantity realised by some function. Dynamic correction is based on solving the inverse function to that which is taken from measurement of the quantity, which means that the output values are equal to the values of the measured quantity. It could be said that the measuring circuit performs tasks of ideal transducer. Assuming that, the measures are performed by AD converter the differential equations takes the discreet form. Now, because of correction occurs in discrete moments only the instantaneous values of the transducer output are predicted.

In general case the described algorithm has a recurrent solution which was described in [15]. First order model is a special case, for which there is no form of recursive algorithm correction and the algorithm has simply form.

The experimental results of methane dynamic correction for the sudden change of the concentration of methane was shown in paper [14]. It can be seen that the algorithm of correction works properly with a delay equal to two sampling periods. This accelerate the measurement almost several times.

Method described in paper [14–16] lead to the conclusion that it is possible the correct dynamic error of penetration of methane by flameproof arrester almost real time, basing only on the instantaneous values of methane concentration inside the pellistor sensor enclosure. Correction is performed on the basis of dynamic correction of the discrete changes of the concentration outside the enclosure, and the result is a significant decrease in time to obtain a result. This method can significantly help to improvement the work safety of miners.

Double channel dynamic correction

In a situation when the dynamic properties of sintered shield changes over time, what happens as a result of the contamination, the use of single channel correction model causes additional errors resulting from the difference between the adopted for the calculation and the actual value of time constant. In this situation, it is necessary to identification the time constant.

The most useful is a method that does not require the use of calibration mixtures, called "blind correction" [11, 12, 13] or double channel correction. The essence of that method involves the parallel operation of two measuring heads with different time constants which values are not known. Software processing algorithm consists in this case of two steps: first self-identification of time constant (or both), and next a correction like that for single channel method. The structure of the measuring setup implementing double channel correction is shown in figure 3.

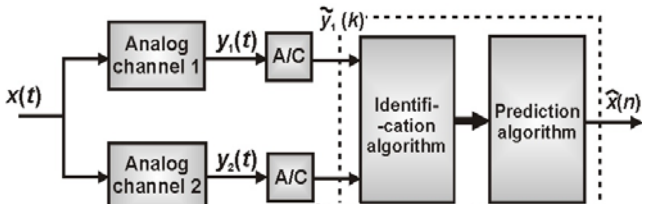

Fig.3. Processing system for double channel correction

Measured signal is brought to the inputs of two analog measuring transducers. Both of them have the same type of dynamic models, but differ in the model coefficients. It was assumed that these are the first order models with different time constants. The actual values of the output signals are sampled with the same frequency for both transducers. The samples are converted by AD converters. Obtained samples are processes by identification algorithm to designate the model coefficients. Then it is realized a correction algorithm similar to single channel correction based on the obtained time constant [16].

Model used in single channel correction need only time constant identification of 1-st order differential equation.

In this case:

(1) $$x(t_i) = y_1(t_i) + T_1 \cdot \dot{y}_1(t_i) = y_2(t_i) + T_2 \cdot \dot{y}_2(t_i)$$

where t_i, i = 1, 2,… is a moment of signal measure by both ADCs with frequency $f_d = T_d^{-1}$, T_d is sampling period. The initial conditions $y_1(0)$ and $y_2(0)$ should be taken into account. Using the results from N successive sampling moments obtained a overdetermined set of equations:

(2) $$\begin{cases} y_1(t_1) + T_1 \cdot \dot{y}_1(t_1) = y_2(t_1) + T_2 \cdot \dot{y}_2(t_1) \\ y_1(t_2) + T_1 \cdot \dot{y}_1(t_2) = y_2(t_2) + T_2 \cdot \dot{y}_2(t_2) \\ \vdots \\ y_1(t_i) + T_1 \cdot \dot{y}_1(t_i) = y_2(t_i) + T_2 \cdot \dot{y}_2(t_i) \\ \vdots \\ y_1(t_N) + T_1 \cdot \dot{y}_1(t_N) = y_2(t_N) + T_2 \cdot \dot{y}_2(t_N) \end{cases}.$$

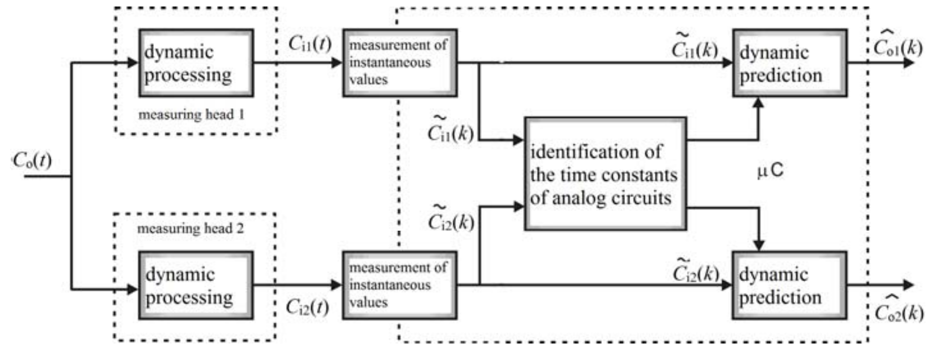

Fig.4. Processing system for double channel correction of methane concentration

It allows to determine the time constants T_1 and T_2 of both measuring transducers. This set of equations must be solved in order to obtain information about the constant T_1 and T_2 in a way that minimizes the errors of identification [13].

In case of methane concentration measurements the both measuring channel has the different time constants but they are described by the same equations. For each of the two measuring circuits (Fig. 4) concentration outside the flameproof enclosure are equal:

(3) $$C_{o1}(t) = C_{o2}(t) = C_o(t),$$

where $C_{o1}(t)$ is the concentration of methane out of the first enclosure, and $C_{o2}(t)$ is the concentration of methane out of the second enclosure. Taking into account (1) and (3) it can be written:

(4) $$T_{s1}\frac{d\,C_{i1}(t)}{dt} + C_{i1}(t) = T_{s2}\frac{d\,C_{i2}(t)}{dt} + C_{i2}(t),$$

where T_{s1} i T_{s2} are the time constants of flameproof shields respectively the first and second channel, and where $C_{i1}(t)$ is the concentration of methane in of the first enclosure, and $C_{i2}(t)$ is the concentration of methane in of the second enclosure. For any two time moments t_1 and t_2 it can be written:

(5) $$\begin{cases} T_{s1}\frac{d\,C_{i1}(t_1)}{dt} + C_{i1}(t_1) = T_{s2}\frac{d\,C_{i2}(t_1)}{dt} + C_{i2}(t_1) \\ T_{s1}\frac{d\,C_{i1}(t_2)}{dt} + C_{i1}(t_2) = T_{s2}\frac{d\,C_{i2}(t_2)}{dt} + C_{i2}(t_2) \end{cases}.$$

Assuming a constant sampling period of methane concentration inside the shield equal to T_d, numbering of sampling moments can be made by the variable k. The methane concentration predicted for the same sampling moments should be identical in both measuring channels for every time instant k:

(6) $$\hat{C}_{o1}(k) = \hat{C}_{o2}(k) = \hat{C}_o(k),$$

Equation (6) determine the predicted values of the measured values (concentration of methane out of the enclosure) in both measuring channels at the same time.

Similar like for the single channel correction [15], the methane concentration can be predicted for each independently measurement channel for any k time moment. For the j measurement channel, where j = 1, 2, methane concentration is determined by the formula:

(7) $$\hat{C}_{oj}(k) = A_{k+1,j}\widetilde{C}_{ij}(k+1) + A_{k,j}\widetilde{C}_{ij}(k).$$

The values of the coefficients $A_{k+1,j}$ and $A_{k,j}$ of equation (7) are calculated from formulas:

(8) $$A_{k+1,j} = \frac{1}{1-\varphi_j}, \quad A_{k,j} = \frac{-\varphi_j}{1-\varphi_j}, \quad \varphi_j = e^{-\frac{T_d}{T_{sj}}},$$

where j = 1, 2.

In order to minimize prediction errors as the final result assumed the average of results from two channels in k moment. Next the predicted value was calculated from several subsequent results.

Result of correction

Experimental results of methane dynamic correction for the sudden change in the concentration of methane was shown in figure 5. Although a small uncertainty of the measurement data there are large errors in the predicted values which is due to the strengthening effect of random errors by the dynamic correction algorithms [23].

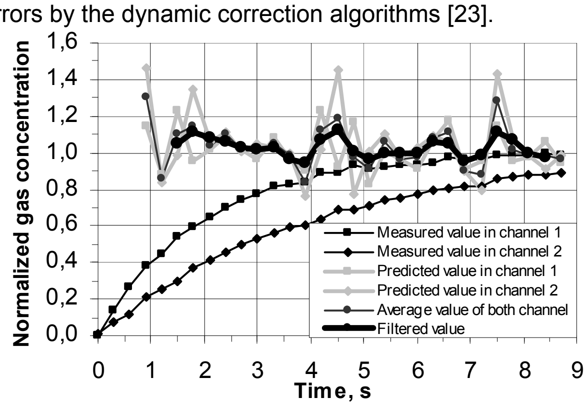

Fig.5. Prediction methane concentration by double channel correction method

Simple averaging algorithm, reduces the final error dynamic correction by nearly half. The time required to obtain a measurement result shortened to less than one second. It is the time required to obtain a three consecutive reconstructed results for the filtration algorithm.

Most important parameter for prediction is the time of receipt of the final result with the required accuracy. The study shows that the developed algorithms provide significant reduction of time to obtain the result. For sample period equal 0.3 s, time of obtain the results is about 1 s for the single channel correction and simple filtration algorithms. In the case of double channel correction this time increases due to the fact that the prediction must be preceded by time constant identification.

Table 1. The calculated times T_{90} and maximum error values Δy_m.

	T_{90} , s	Δy_m, %
The answer to the step change in first channel	4.8	86
The answer to the step change in second channel	9.3	91
Results of prediction in first channel	0.6	8
Results of prediction in second channel	0.6	38
Result after averaging from both channels	0.6	22
Results after filtration	1.2	13

The maximum dynamic error in the absence of correction is approximately 90%. However, after the algorithm predicting the dynamic error decreases to about 10% (results after filtration - simple averaging). Other tested filtration methods did not give much better results but prolonged time to obtain them.

Conclusions

Described correction method may be used to reduce the time for obtaining the result of measurement of the methane concentration after the step change in the mining conditions. Correction is performed on the basis of dynamic correction of the discrete changes of the concentration outside the enclosure, and the result is a significant decrease in time to obtain a result. In the coal mines pellistor shields might soil, which leads to changes in the dynamics of methane diffusion.

Double channel correction method can be used in a situation where the time constant of the model is changing or is not known. It is ideal in mine operating conditions. In such a case requires the use of two measuring heads with shields with different time constants. The methods can be used on an almost in real time, which means that the execution time of correction algorithms is so short that it does not introduce a significant delay in obtaining the final result.

Method described in this paper lead to the conclusion that it is possible the current dynamic error correction of penetration of methane by flameproof arrester, based on the instantaneous values of methane concentration inside the enclosure measured using pellistor sensor. This method can significantly help to improvement the work safety of miners.

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