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NEW INSTRUMENTS AND METHODS FOR ANALYSING THE COAL-METHANE SYSTEM

NORBERT SKOCZYLAS, MATEUSZ KUDASIK, MIROSŁAW WIERZBICKI, TOMASZ MURZYN

The Strata Mechanics Research Institute of the Polish Academy of Sciences,
e-mail: skoczylas@img-pan.krakow.pl, kudasik@img-pan.krakow.pl,
wierzbicki@img-pan.krakow.pl, murzyn@img-pan.krakow.pl

Abstract: The authors of the present paper designed and constructed a prototype of an instrument which enables fully automated determination of the desorbable methane content and effective diffusion coefficient in underground conditions. Due to microprocessor analysis of the recorded data and the application of the mathematical model of the diffusion process, it is possible to automatically determine the amount of methane whose release from a coal sample occurred before the sample was placed within a measuring instrument. It is also possible to carry out follow-up extrapolation of the recorded data so the time duration needed to determine reliable results can be reduced. The instrument was tested and optimized, and a number of copies sufficient for performing underground tests were constructed. The concept of the instrument represents a totally new approach to the observation of gas release from a coal sample. Instead of short-period measurements, virtually the whole process of methane release from coal is registered and analysed. This is possibly due to the use of a grain fraction lower than one mm which is presently applied for the sake of evaluating the methane-bearing capacity and desorption intensity.

Key words: *desorption, methane, carbon dioxide, coal, outburst, diffusion*

1. INTRODUCTION

In the light of the Polish Labour Code, the employer – being responsible for providing a safe working environment – is obliged to protect the health and lives of employees, ensuring safe and hygienic working conditions via the proper application of scientific and technological achievements. Although mining is counted among most traditional sciences, technological progress makes it possible to introduce new metrological solutions into mining practices.

In order to properly construct a metrological instrument, one needs to understand the physics of the process which is going to be measured. Usually, investigations of the coal-methane system – or, more generally, the coal-gas system – concern the analysis of steady states or dynamic processes.

The first group encompasses the values of sorption capacities investigated under various conditions. In particular, these can be: the total sorption capacity under the coal seam methane pressure, the sorption capacity under the methane pressure of 1 bar, and the desorbable content of methane in coal (Wierzbicki M. [12]). These parameters are best interpreted in relation to the methane-bearing capacity, as this makes it easier to estimate the extent to which a given seam is prone to gasogeodynamic phenomena (Skoczylas N. [9]). To determine the parameters in question, one should wait until the sorption processes reach the asymptotic value.

The second group are the parameters describing the transportation of gas. In this case, it is necessary to perform a long-term analysis of the processes of the transportation of gas through a porous structure during the process (Wierzbicki M. [14]). The basic parameter describing the kinetics of methane release from a coal sample is the diffusion coefficient.

In the Polish mining industry, as well as in many other countries, where CH_4 or CO_2 are found in coal seams, it is a common practice to perform a quick determination of the parameters whose values depend both on the value of the sorption capacity and on the parameters of the kinetics of methane release (Wierzbicki M., Skoczylas N. [13]). An example of such a parameter is the desorpion intensity index. It needs to be emphasized, however, that the analysis of the value of this parameter does not allow us to state with full certainty if the measured value is the result of high methane-bearing capacity, or maybe a high diffusion coefficient. These parameters can "neutralize" each other, yielding – in consequence – typical results in untypical mining and geological situations.

2. THE MODEL OF THE PROCESS OF ACCUMULATION/RELEASE OF METHANE FROM A GRANULAR COAL SAMPLE

While constructing measuring equipment for the analysis of methane release from coal samples, one should take into account the following aspects of the physics of the process: the desorption proper occurs almost instantaneously (Gawor M., Skoczylas N. [3]), and the filtration flow of gas between the sorbent grains is so fast – in comparison with the diffusion occurring inside the grains (King, Ertekin, [6], Harpalani, Schraufnagel [5], Crosdale et al. [2]) – that it is the diffusion process that decides about the kinetics of gas release. Thus, it can be concluded that when we observe the temporal course of methane release from a coal sample, we analyse in fact the diffusion process (Harpalani S., Chen G. [4]).

The most frequently used physical model for determining the effective diffusion coefficient is based on the unipore model (Xiangchun Li et al. [15]).

The changes in the distribution of the concentration of the particles of the deposited gas are described by means of the following formula

$$\frac{\partial c(r,t)}{\partial t} = \frac{D}{1+\Gamma}\nabla^2 c(r,t) = D^*\nabla^2 c(r,t), \qquad D^* = \frac{D}{1+\Gamma}, \tag{1}$$

where

D^* is the effective diffusion coefficient,

Γ is the Henry isotherm coefficient,

$c(r, t)$ is the concentration of the sorbents.

The solution to the equation used in the unipore model can be found in the works by Crank [1] and Timofeev [11]. Under specific initial and boundary conditions, it assumes the following form

$$m(t) = \frac{6M}{\pi^2}\left(\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D^* t}{R^2}\right)\right) \tag{2}$$

where

M [g] is the total mass of gas deposited in grains,

$m(t)$ [g] is the mass of gas deposited at moment t,

R [cm] is the substitute grain radius, for a sample of the grain fraction investigated, determined on the basis of the formula

$$R = \frac{1}{2}\sqrt[3]{\frac{2\cdot d_1^2\cdot d_2^2}{d_1+d_2}} \tag{3}$$

where d_1 and d_2 are the boundaries of the size of grains of the grain fraction under investigation.

3. THE NEW CONCEPT OF THE MEASUREMENT OF THE PARAMETERS OF THE COAL-METHANE SYSTEM

The concept of the construction of the instrument discussed represents a totally new approach to the observation of gas release from a coal sample. Instead of short-period measurements, virtually the whole process of methane release from coal shall be registered and analysed. This is possible due to the use of a grain fraction lower than one mm which is presently applied for the sake of evaluating the methane-bearing capacity and desorption intensity. According to the calculations (formula (2)) and the initial research, with the grain fraction of ca. 0.2–0.3 mm, the time of the measurement will be ca. 24 hours. Due to the extrapolation of the course, performed with use of the mathematical model of the diffusion process, the approximate results shall be known within a few hours.

Table 1. The basic characteristics of the instrument, as well as of the measurement method

	New measurement concept	Manometric desorbometer
Grain fraction [mm]	0.2–0.25	0.5–1.0
Substitute radius [mm]	0.11	0.35
Duration of measurement	ca. 24 h	2 minutes
Measured value	The desorbable methane content, the diffusion coefficient	The desorpion index (dependent on the desorbable methane content and the diffusion coefficient)
Measurement method	The electronic measurement with the digital processing of the results – the cyclic measurement of the differential pressure within the range of 0–1.25 kPa	The analog measurement of the differential pressure on a U-tube within the range of up to ca. 2kPa

The basic characteristics of the instrument, as well as of the measurement method, are presented in Table 1. Additionally, for each characteristic, an equivalent from the desorbometric method is given.

The adoption of the mathematical model of the diffusion process will also make it possible to reliably correct the so-called loss of gas, i.e., the amount of methane released from the sample between the moment when the drilling of the proper fragment of the research borehole begins and the moment when the measurement starts. Here, it is essential that the value of the correction shall be a value determined physically, individually in the case of each measurement – and not a general, tabular factor.

4. THE CONCEPT OF THE ELECTRONIC MEASURING INSTRUMENT FOR THE EVALUATION OF THE DESORBABLE METHANE CONTENT IN COAL AND THE EFFECTIVE DIFFUSION COEFFICIENT

The automated analyser of the diffusion process operates on the basis of an indirect measurement of the amount of methane released from a coal sample, performed by means of registration of the changes in the pressure in a chamber of a known volume (Fig. 1).

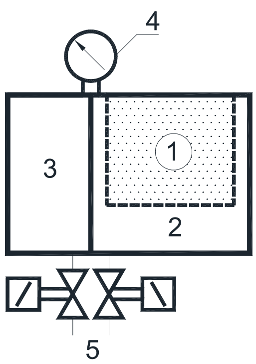

Fig. 1. The automated analyser of the diffusion process

The notable characteristics of the analyzer are as follows: the instrument has two chambers (2, 3) between which the differential pressure is measured. A differential pressure converter of a very high sensitivity (4) is used. Two miniature electrovalves (5), pneumatically connecting the instrument chambers with the external environment, are also used. During the measurement, the instrument performs – in a cyclic manner – the sequence described below, whose beginning is determined by the hermetic sealing of the container (1), with coal saturated with methane inside the measurement chamber (2):

- the beginning of the cycle, both micro-electrovalves are open, the differential pressure between both chambers is zero,
- the micro-electrovalves are closed; due to the release of gas from the coal sample (1), the differential pressure inside the chamber with the sample (2) increases in relation to the reference chamber (3),
- the readings of the pressure converter (4) are registered until the differential pressure value approaching the measuring range of the differential manometer is reached,
- the end of the measurement cycle – the electrovalves are temporarily re-opened, the cycle begins again.

The concept of an instrument with two chambers, coupled with a cyclic mode of the instrument performance, makes it possible to apply a precise differential converter and to ensure quasi-isobaric conditions of the experiment. Therefore, the instrument is capable of working within a wide measuring range of the converter; also, the model of the sorbing gas diffusion in a porous medium can be applied. In the case where an absolute converter is used, a minor increase in the pressure caused by methane release would be measured with a converter whose range would exceed 1 bar. This would necessitate giving up on the quasi-isobaric quality of the measurement (an increase in pressure within the measuring chamber would have to be significant), or generate noises difficult to separate in relation to the measurement of the kinetics of methane release. Using a differential converter with a terminal open to the external environment is, in turn, impossible. This is due to the specific characteristics of the environment in which the instrument operates: it is an excavation, where complex ventilation systems, resulting in dynamic, local pressure fluctuations, are used. The two-chamber system has also an advantageous effect on the compensation of the impact of temperature changes on the registered results. If we assume that a change in the temperature of the external environment entails a uniform change in temperature in the instrument area, the result will be a proportionally equal change in pressure in both chambers. This will have no impact on the value of the differential pressure.

In order to present the structure of the instrument discussed, three-dimensional visualizations of the design were generated (Fig. 2). Due to the possibility of rendering engineering structures with translucent effects, all connections – and, what follows, the coop-

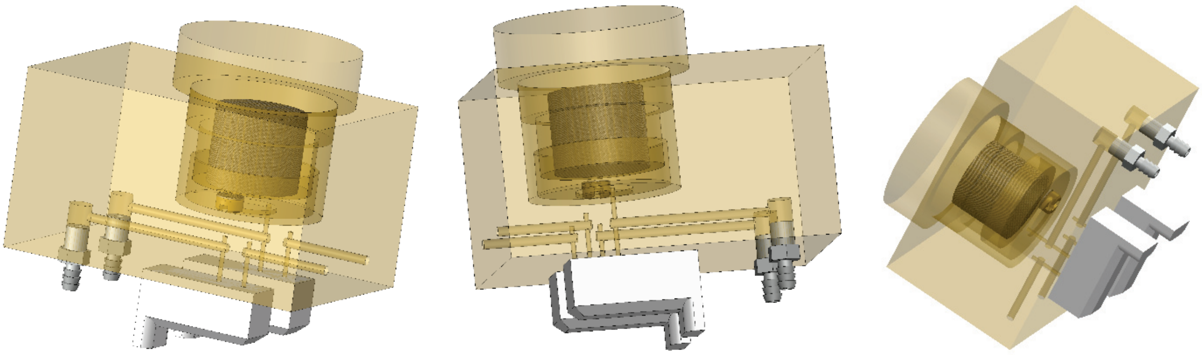

Fig. 2. The 3D visualizations of the discussed metrological instrument

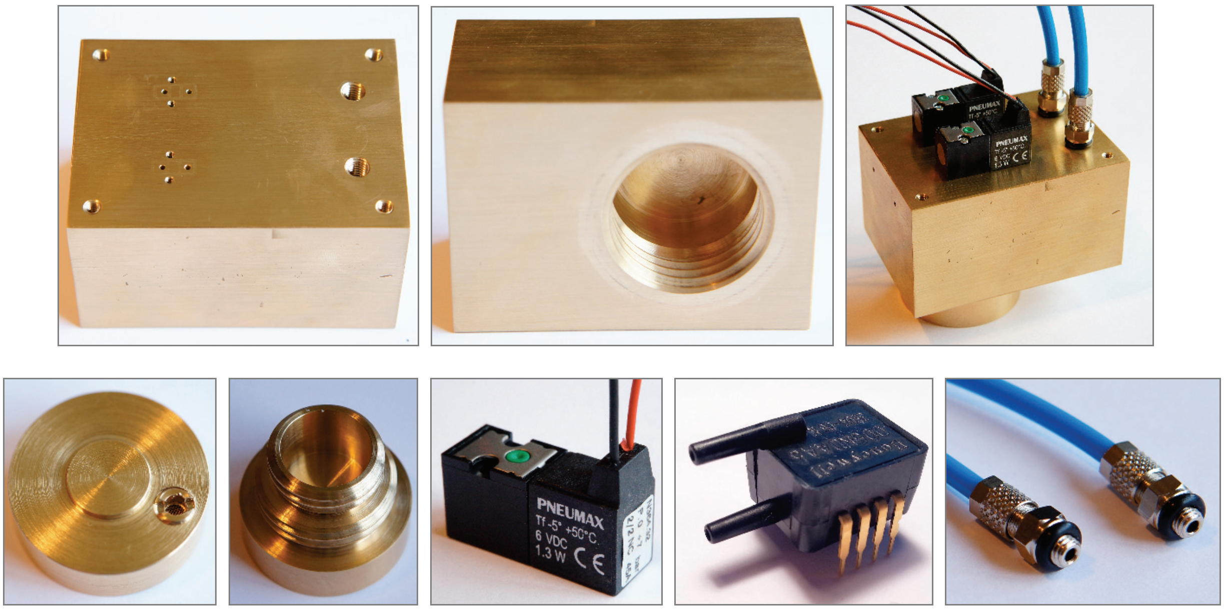

Fig. 3. The photographs of the metrological instruments discussed and their essential components

eration between the particular components of the instrument – can be easily demonstrated.

The photographs in Fig. 3 show the measuring instrument, as well as its most important components. In the picture showing the casing, the mounting holes of the micro-electrovalves and the inlets of the pneumatic links are visible. The container for a coal sample is secured with a lid once the coal material is placed inside it. In order to ensure a free flow of the desorbing gas and prevent the coal material from dispersing beyond the container, a small opening was made in the lid. In the opening, by means of a sleeve, a strainer was placed. The holes of the strainer are much smaller than the size of the coal grains belonging to the grain fraction investigated. Apart from the constructional elements, the prototype was equipped with an electronic system triggering the micro-electrovalves with an electric signal.

5. BASIC TESTS ILLUSTRATING THE FUNCTIONING OF THE INSTRUMENT AND ITS METROLOGICAL CAPACITIES

The leaktightness of the electronic instrument was tested. To this end, instead of the coal material, some ballotini were placed in the container (lack of sorption). Subsequently, the overpressure (in relation to the reference chamber) of 1 kPa was created in the measuring chamber. The instrument thus prepared was placed inside a thermostatic chamber, and the readings of the pressure converter were recorded for 24 hours. The results obtained are presented in Fig. 4. The leaktightness of the instrument is satisfying – there were virtually no pressure changes throughout the duration of the recording process. The next chart (Fig. 5) presents a direct record from a differential converter. The registered phenomenon was methane release from a coal sample representing a 0.2–0.25 grain fraction, previously saturated with methane under the pressure of 5 bar. Both the saturation process and the preceding outgassing in vacuum (ca. 10 Pa) lasted 24 hours. The chart presents the recording process for the time period between the 1st and the 6th hour of the desorption/diffusion processes. Once the upper measuring range of the pressure converter was reached, the control system would open both electrovalves for ca. 0.2 s, which "zeroed" the differential pressure in the measuring chamber in relation to the reference chamber. The measuring process was cyclical. It is easy to notice that, during observation, the duration of a single cycle increases noticeably. This, of course, is consistent with the physics of the phenomenon – the speed with which methane is released from coal (in time) is reduced in an asymptotic manner.

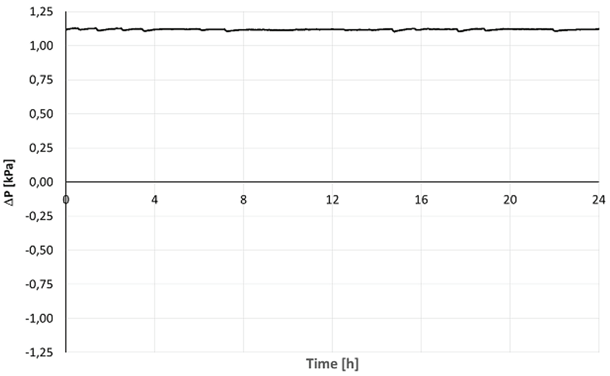

Fig. 4. The leaktightness test, the 24-hour observation of the overpressure readings under thermostatic conditions

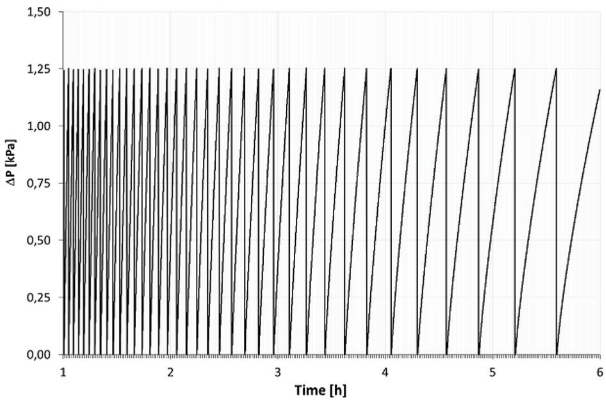

Fig. 5. The direct pressure record from a differential converter

Whenever the value of the saturation pressure was around 5 bar (Skoczylas N. [8], [10]) (this is a typical value of the seam pressure for the Upper Silesian Coal Basin), the number of cycles during the measurements exceeded 100. Due to the proper geometry of the measuring chambers and the appropriate selection of the sample mass, both the analysis and recording of the process could be simplified. Only the time when consecutive cycles begin can be recorded, and the amount of gas released from coal during one cycle is regarded as constant. This is very convenient in the light of the analysis of the results obtained, in particular when a microcontroller of a limited computing capacity is used. If the above-mentioned assumption is adopted, it is easy to generate – on the basis of the chart (Fig. 5) – the chart that is the end one (Fig. 6).

As part of the tests, the process of methane release from coal was observed. The observation was registered with the prototype constructed and a reference instrument – the IGA sorption scale (Fig. 7). The registered courses reveal close similarity. This guarantees that the values of the diffusion coefficient determined with both instruments will be similar (they do not depend on the amplitude, but on the shape of the curve).

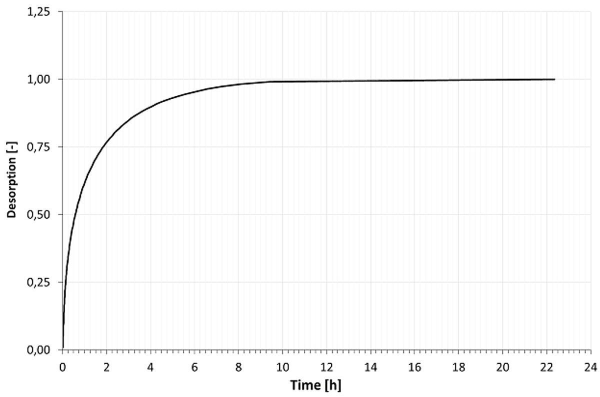

Fig. 6. The process of methane release from coal registered with the prototype of the instrument

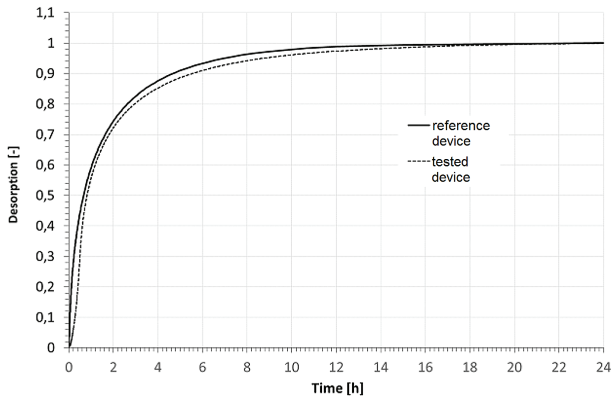

Fig. 7. The preliminary validation of the results in relation to the IGA device

The authors of the project firmly believe that the discussed prototype is a very promising instrument. It can be presumed – with a high degree of certainty – that its further tests and modifications will yield the expected results.

6. THE CORRECTION OF THE "LOSS OF GAS"

While observing the process of methane release from a coal sample, the researchers noticed that – in the initial (for $t < 300$ s) period of time – the speed of methane release is proportional to the time element. Similar remarks can be found in relevant scientific sources (Pillalamarry M. et al. [7]). On the basis of this information, the authors estimated the amount of gas released between the start of the drilling of the appropriate section of a research borehole and the airtight sealing of the measuring instrument followed by the beginning of the recording process.

The instrument starts working when the drilling of the above-mentioned section of the research borehole begins. The bore dust from the borehole shall later be analysed (moment $t_0 = 0$, the "start" button of the instrument, the instrument starts recording the time, one waits for the change of readings of the differential pressure converter). For the first several dozen seconds (this is the time when the bore dust is released from the borehole, to be subsequently sieved and placed inside the instrument), the measuring instrument waits for the start of the methane release measurement. Then, the measurement of methane release begins, together with the recording of the consecutive time periods during which the differential pressure values in the measuring chambers became equal as a result of short-time openings of the electrovalves. The start of the recorded data is shown in Fig. 8.

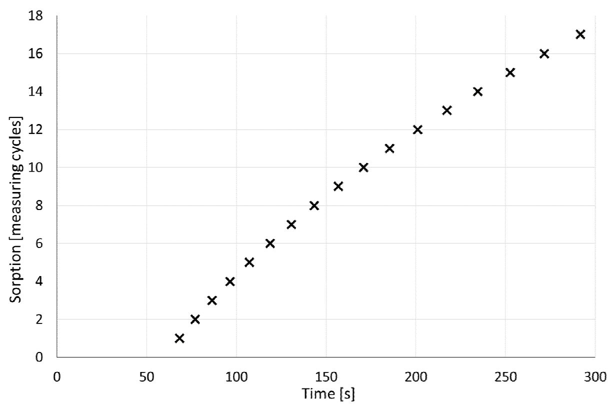

Fig. 8. The starting times of consecutive measurement cycles during the initial 300 seconds of the process of the observation of methane release

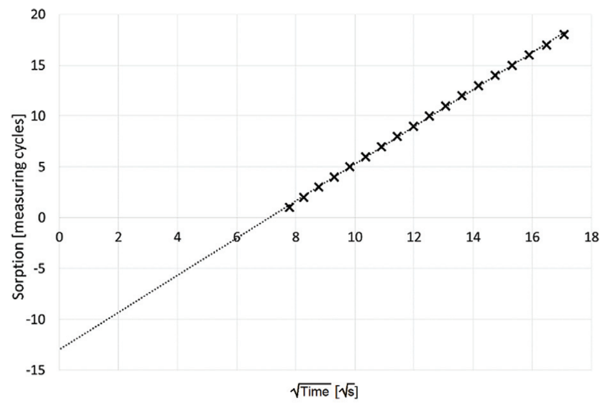

Fig. 9. The initial 300 seconds of the measurement, the domain of the function subjected to root extraction

In this case, the period of time between starting the instrument (and, what follows, the moment when the drilling of the section of the borehole which is of interest to us began – this, in turn, being the starting point of the release of methane from the sample, in the physical sense) and the start of the measurement was ca. 70 s. After the instrument has registered the consecutive temporal moments corresponding to the openings of the electrovalves, up to ca. the 300th second of the observation, the correction of the lost gas is performed. The times of the openings of the electrovalves are subjected to root extraction. Subsequently, the parameters of the linear regression are calculated, on the basis of the following classic equations

$$a = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2}, \quad b = \frac{1}{N}(\Sigma Y - a\Sigma X) \qquad (4)$$

(where X stands for the times of the openings of the electrovalves, Y represents the indices of the consecutive openings (1, 2, 3 ...), N is the number of openings up to $t = 300$ s, a is the directional coefficient of a straight line, b is the value of the function for $t = 0$) – cf. Fig. 9. From the point of view of the analysis of the issue, what is interesting to us is the value of the coefficient b of regression. This is the searched amount of the gas which had been released before the sample was placed within the instrument.

7. SUMMARY

The instrument proposed by the authors may have a complementary role to the measurement methods concerning the coal-gas system that have been used so far. The potential benefits resulting from the design and the properties of the proposed instrument are as follows:

- the measuring instrument was constructed on the basis of an innovative idea, adopting the concept of a two-chamber structure with a sensitive differential pressure converter and micro-electrovalves,
- the measuring range of the instrument is virtually unlimited,
- the way the instrument was designed and built is conducive to levelling the impact of temperature changes,
- the result of the measurement is a set of parameters whose determination with the methods that are available at present is possible only under laboratory conditions,
- the built-in microcontroller which controls the functioning of the instrument makes it possible to determine the effective diffusion coefficient, due to the implementation of the mathematical model,
- the desorbable methane content and the effective diffusion coefficient are parameters with a huge informative potential, which is particularly important in the light of the evaluation of gasogeodynamic phenomena.

The concept of the instrument was submitted to the Patent Office of the Republic of Poland. At present, a final bout of copies is being developed. Subsequently, the instruments shall be tested in underground conditions, i.e., in mines.

ACKNOWLEDGEMENTS

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