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MAREK GAWOR*, JÓZEF RYSZ*

MEASUREMENTS OF TIME-VARIANT GAS PRESSURE IN POROUS MEDIA

POMIARY ZMIENNEGO W CZASIE CIŚNIENIA GAZU W OŚRODKACH POROWATYCH

This article presents a critical analysis of a commonly-used method of time-variant gas pressure measurements in the pores of coal briquettes. In case of transient-state measurements a considerable reduction of the sensitive volume of the transducer is neccesary. Some results of dynamical response of various sensitive volume transducers are presented.

An appreciable reduction of the sensitive volume in sensors allows the time variations of gas pressure in the pores during the stage of briquette decompression to be monitored, that is about 2 ms before a crack should appear. A sensor with a sensitive volume of less than 0.5 mm^3 registers very distinct pressure changes throughout this time interval. Measurements of gas pressure in the cracks, following the briquette breaking, can be taken with pressure sensors with a the sensitive volume of up to several cubic millimetres.

Key words: dynamic pressure measurements, rarefaction wave, time constant, rock and gas outbursts

W artykule przedstawiono krytyczną analizę stosowanego powszechnie sposobu pomiaru zmiennego w czasie ciśnienia gazu w porach brykietów węglowych. Do badań wykorzystano prasowane z drobnych ziaren węgla brykiety nasycone gazem (CO_2 lub He) do ciśnienia rzędu kilku dziesiątych MPa (Gawor et al. 1994). Po nagłym obniżeniu ciśnienia następuje rozpad brykietu. W czasie destrukcji mierzono ciśnienie gazu na pobocznicy brykietu, jego odkształcenie i temperaturę.

Rzetelny pomiar wymienionych parametrów termodynamicznych jest trudny do realizacji, ponieważ zjawisko jest szybkie (prędkość fali rozrzedzeniowej dochodzi do 100 m/s, a fali kruszenia do 10 m/s). Dlatego użyte do eksperymentu przetworniki ciśnienia, odkształcenia i temperatury muszą być szybkie i mieć dobry kontakt ze szkieletem brykietu. Do pomiaru temperatury wykorzystano specjalnie skonstruowane (o cienkim złączu odniesienia) termoelementy konstantan-manganin. Odkształcenie mierzono tensometrami oporowymi (Rysz 1996) wprasowywanymi w brykiet podczas jego formowania. Bardzo małe liniowe rozmiary tensometrów i te same właściwości sprężyste co otaczającego je węgla umożliwiają wykonanie prawie punktowych, bez opóźnień w czasie pomiarów odkształceń.

Ciśnienie gazu mierzono za pomocą piezorezystancyjnych czujników ciśnienia z krzemową membraną, na której naparowany jest mostek Wheatstone'a. Przebadano kilka typów takich czujników.

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* INSTYTUT MECHANIKI GÓROTWORU PAN, 30-059 KRAKÓW, UL. REYMONTA 27

Zmieniano ich konstrukcję tak, aby maksymalnie zmniejszyć objętość „martwą" oddzielającą membranę czujnika od powierzchni brykietu (rys. 2). Wykazano, że zmniejszenie tej objętości prowadzi do zmniejszenia stałej czasowej czujnika, a więc powiększa pasmo przenoszonych zmiennych w czasie ciśnień.

Radykalne zmniejszenie objętości martwej przetwornika umożliwia śledzenie zmian w czasie ciśnienia gazu w porach w fazie rozprężania się brykietu, tj. około 2 ms przed momentem pojawienia się szczeliny. Zbudowany czujnik o objętości martwej mniejszej niż 0,5 mm^3 rejestruje wyraźne zmiany ciśnienia w tym przedziale czasu (rys. 8). Mierzone ciśnienia są prawdopodobnie zawyżone w porównaniu z rzeczywistymi wartościami ciśnień w porach.

Większą dokładność odtworzenia rzeczywistych zmian ciśnienia gazu w porach można uzyskać stosując miniaturowe przetworniki ciśnienia, których membrany mają wymiary dziesiątych części milimetra. Pomiar ciśnienia gazu w szczelinach po pęknięciu brykietu może być wykonany za pomocą czujników o objętości martwej do kilku milimetrów sześciennych.

Słowa kluczowe: dynamiczne pomiary ciśnienia, fala rozrzedzeniowa, stała czasowa, wyrzuty gazu i skał

1. Introduction

Rock and gas outbursts occurring when the rock mass is disturbed by mining operations have been regarded as a major hazard for over 150 years and constitute a research problem. Extensive laboratory tests and theoretical studies have so far failed to provide a full description of this process. Some aspects are outlined in the monograph by (Lama, Bodziony 1996). Laboratory tests involving briquette disintegration due to the rapid decompression of coal-saturating gas (Bodziony et al. 1990; Ujihira et al. 1985) and pictures taken with fast camera (Gawor et al. 1994) reveal that coal disintegration is a discontinuous process. It can be easily seen that flake-like coal layers are separated from the coal body and travel with the flowing gas.

An explanation of the discrete disintegration process can be found in Litwiniszyn's hypothesis (Litwiniszyn 1994) which states that an outburst is initiated by a rarefaction shock wave. Another explanation has been suggested by Ujihira (Ujihira et al. 1985) and Topolnicki (Topolnicki 1999). According to them, an outburst is a gas-geodynamic process in which the gas seepage from a porous medium through an open surface (a front section) generates tensile forces in the skeleton (core). The tensile force is a non-monotonic function of the distance from the front. As the gas continues to flow, the value of the tensile force increases and the maximum point moves away from the front surface. When the tensile stress exceeds the coal strength, the skeleton breaks and a layer of coal is separated from the body and torn off. After that subsequent coal layers are separated as the process is repeated over and over again.

Both hypotheses highlight one important aspect of the process — i.e. its discontinuity. At regular time intervals, the initial conditions of gas pressure prevailing in the crack appearing in the solid rock body recur, and another crack at distance Δx is produced. In order to determine which hypothesis is right a research program is required to register local variations of gas pressure in pores, strains, and temperatures. Reliable measurements of these thermodynamic parameters present certain difficulties, since the process is really fast and has a local character. The velocity of the rarefaction wave in the skeleton (Gawor, Rysz 1998) can be as high as 100 m/s while the rate of briquette disintegration reaches 10 m/s. The temperature transducers used in these measurements must also be really fast-responding and retain an adequate thermal contact with the skeleton. Strain gauges ought to be small in relation to the coal flake dimensions while their elastic properties should be the same as that of the surrounding coal (Rysz 1996). The requirements as to pressure transducers will be discussed in the next sections.

2. Measurement of fast-changing gas pressures in the pores

There are several techniques for gas-pressure measurement and electrical techniques seem best for the measurement of time-variant pressures. Piezo-electric transducers and silicon piezo-resistant transducers are in wide use in laboratories and in engineering applications. Piezo-electric transducers utilise the electric charge appeared on the walls of squeezed quartz crystals or ceramic plates. The charge is proportional to the pressure applied to the crystal wall and appears only when the pressure changes. As soon as the pressure is stabilised, the charge is dissipated due to leakage conductance. These transducers are commonly used for the measurement of fast-changing pressures, such as those in combustion chambers of heat engines. The limit to the upper frequency band of pressure variations is the natural frequency of oscillation of the crystal. Manufacturers state that these limiting frequencies may reach 1.5 MHz.

New-generation piezo-resistance pressure transducers are manufactured using micro-electronic technologies. A silicone membrane, whose thickness is precisely designed to accord with the intended measurement range, is used to seal a reference-pressure chamber. Because of membrane deflection caused by changes of external pressure, the bridge circuits, made of four resistors, become imbalanced. These four resistors are made on the silicone surface using the vacuum evaporation technique. At the same time special resistors are engineered, to provide compensation for the effects of temperature. Transducers are manufactured by several firms. They have good linear characteristics, small hysteresis, provide for adequate temperature compensation and various measurement ranges are available. They are made as differential, absolute and gauge-pressure sensors.

The silicon membrane type with implanted resistors is most sensitive to chemical agents and has poor mechanical resistance. For this reason manufacturers provide a silicone gel coating or sealed metal or plastic casings. A typical pressure transducer in a casing has the form of a cylinder 19.8 mm in diameter, the bottom section being made of a folded membrane 15 mm in diameter. According to the manufacturers' data, the time-constant for such transducers is 0.5 ms. At he first glance it seems that such transducers are well suited for measuring time-variant gas pressures in briquette pores. However, a closer analysis of the conditions in which the measurements are to be taken reveals that this is not the case.

Fig. 1 shows schematically how a pressure transducer type SSC301AA (Data Instruments) can be fitted in position. In the wall of the briquette pipe there is a seat 20 mm in diameter. The sensor is fixed in place and secured with a nut. The bottom section of the seat is flat. The distance between the middle, flat section of the membrane and the bottom varies from 0.4 to 0.5 mm, while the distance between the membrane folds and the bottom is about 0.1 mm. An opening 2 mm in diameter is bored along the bottom axis. As soon as the briquette is formed, gas contained in the briquette pores may come into contact with the gas contained in the volume V_m confined by the seat walls, the sensor membrane and the surface of the exposed briquette. This contact is possible through surface S.

V_m denotes the sensitive volume of the sensor which actually measures the pressure p_m of gas contained in it. Gas pressure in pores p_p equals the pressure measured in steady states only. Each change of gas pressure in the coal pores leads to gas seepage from the pores to the volume V_m or in the opposite direction. The measure of the rate of sensor response (i.e. the time constant τ) to a change of gas pressure in the pores is the quotient of the sensitive volume V_m and the stream of gas Q flowing from the briquette pores through surface S, right to the sensitive volume V_m:

$$\tau = a\frac{V_m}{Q} \tag{1}$$

where:

a — proportionality factor.

This formula, however, can be only used for the qualitative evaluation of the dynamic properties of sensors used in measurements of gas pressure in the pores. Measuring the time-constant of the pressure sensors, (i.e. the time of response to rapid changes in the values of the measured quantity) is not possible, because such rapid pressure changes in the pores cannot be produced. The analysis of formula (1) suggests only one method of shortening the response time, that is, through reduction of the sensitive volume V_m. However, after a briquette with porosity Ψ is formed and saturated with gas, the value of the denominator in (1) cannot be further controlled.

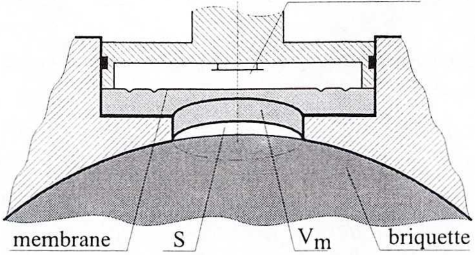

Fig. 1. Installing the pressure sensors

Rys. 1. Schemat mocowania przetwornika ciśnienia

For several years the Laboratory of Flow Metrology in the Strata Mechanics Research Institute PAN has been engaged in research programs involving the measurement of gas pressures in pores. From the start very attempts were made to reduce the sensitive volume of the pressure sensors. The void between the membrane and the seat bottom was filled with silicone lubricant, Fig. 2a. The sensitive volume without the lubricant was estimated to be $V_{m1} = 74$ mm^3. When the lubricant is present it may be reduced to $V_{m2} = 6.0$ mm^3. Such a significant reduction of the sensitive volume did not appreciably affect the pressure variation patterns obtained when the briquette was decompressed prior to its disintegration. Deposition of lubricant on the membrane is not an easy task; it requires a certain skill while the results may not always be reproducible. When too much lubricant is deposited, it may block the briquette pores and no pressure changes will be registered. If the amounts of lubricant are too small, the sensitive volume will not be effectively reduced. In such sensors it is not possible to have a sensitive volume of less than 6 mm^3.

To effectively reduce the sensitive volume, a sensor with the smallest possible membrane area should be applied and positioned very close to the coal surface. The ideal solution would be the sensor type CQ-030 manufactured by Kulite, where the membrane is 0.76 mm in diameter and its natural frequency is 1.5 MHz (Kulite 1992). However, because of insufficient funds the hard and time-consuming job of adapting cheaper sensors so that they meet these conditions is necessary.

Lucas Novasensor is a manufacturer of small absolute-pressure sensors type NPP-301, which are relatively cheap and have the most favourable parameters. A silicone membrane sealing the reference-pressure chamber is a square with side 1 mm (Fig. 2b). The transducer proper is glued to a plastic casing inside a small indentation, which also houses the metal ends of the electric leads, connected via gold wires to the ends of resistors (strain gauges) implanted on the silicone membrane. The whole indentation is covered with silicone gel to protect the gold wires and the silicone plate from damage. The gel surface constitutes the membrane proper which transfers the measured gas pressures onto the silicon transducer. The sensor described here is a rectangular prism, with a base 3.8 × 5.0 mm and 2.1 mm thick. It can be easily fitted in metal casings matching the seats of sensors manufactured by Data Instruments. The detailed arrangement is shown in Fig. 2b. In the cylindrical section there is an opening 8.5 mm in diameter and a small hole 1.5 mm in diameter is bored in the cylinder bottom, 0.5 mm in thickness. A sensor manufactured by Lucas is glued into this opening in such a way that the distance between the sensor bottom and the gel surface is kept to a minimum. The sensitive volume of the indicated sensor (Model b) is 3.3 mm^3. However, tests have revealed that this volume is still too great. Sensors fitted in seats 20 mm in diameter cannot have a sensitive volume of less than about 3 mm^3. That is the volume of a hole 2 mm in diameter bored in the briquette pipe wall. A pressure-sensor must be fixed inside a body, which is in direct contact with the coal surface.

Owing to the convenient arrangement of the electro-conductive metal paths on the sensor body (sensor type NPP-301, manufactured by Lucas), the body can be easily ground to remove unnecessary portions and leaves only a cylinder about 4.0 mm in

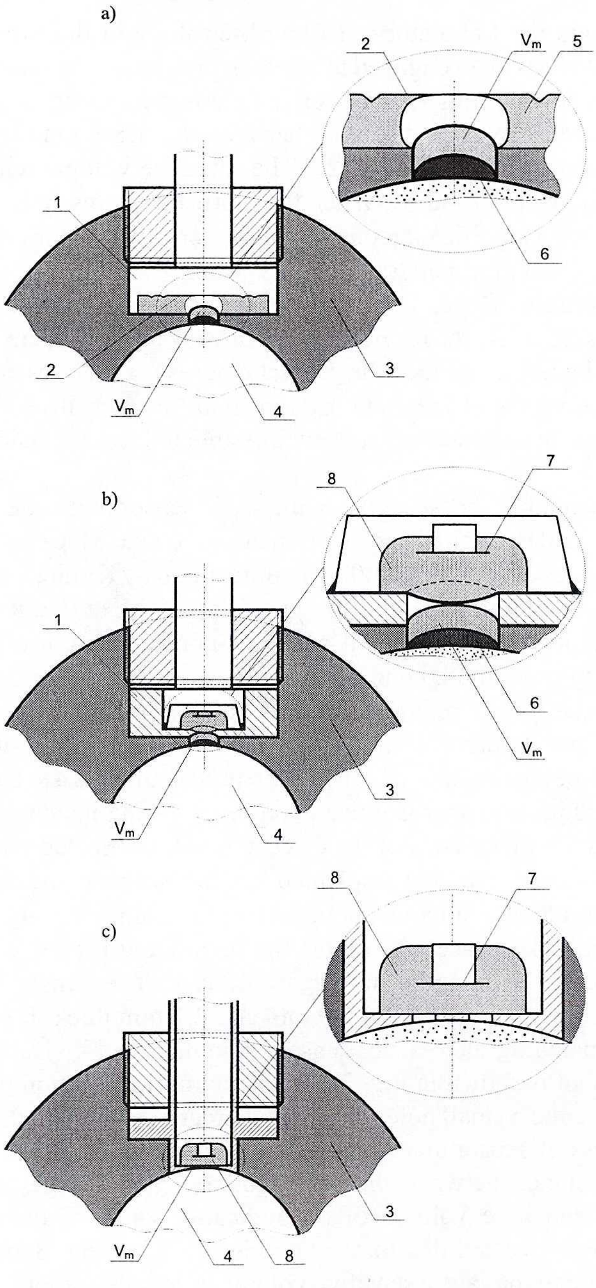

Fig. 2. Installing the pressure sensors in the pipe wall
1 — sensor body, 2 — membrane, 3 — briquette pipe wall, 4 — briquette,5 — lubricant, 6 — briquette side surface, 7 — silicone membrane, 8 — silicone gel, V_m — sensitive volume

Rys. 2. Schemat montażu przetworników ciśnienia w ścianie brykieciarki
1 — korpus przetwornika, 2 — membrana, 3 — ścianka brykieciarki, 4 — brykiet, 5 — smar, 6 — pobocznica brykietu, 7 — membrana krzemowa, 8 — żel silikonowy, V_m — objętość martwa

diameter. Inside this cylinder there is the sensor proper, covered with gel, in the bottom are exposed metal terminals to which the wires providing the connection to the measuring circuit can be soldered. A brand new cylinder has to be ground very carefully; the use of a microscope is recommended. Utmost care must be taken to protect the gel layer, otherwise the gold wires can be broken and sensor will be damaged.

A cut-out sensor proper is fitted in the body, whose dimensions are the same as those of bolts used for securing the thermocouples and strain gauges (Gawor, Rysz 1998), selected details are shown in Fig. 2c. The sensor body is a cylinder 7 mm in diameter. The bottom is not flat, it was ground so that when inserted into the seat, it adheres closely to the convex briquette surface. A small hole 1.5 mm in diameter is bored in this bottom. The sensing element is glued to the body, similar to model b. Silicone oil is used to ensure gel swelling. As a result, the pressure sensor has a stiff front surface made of steel adhering closely to the briquette side wall. In the middle of the front surface is an opening 1.5 mm in diameter, sealed with silicone gel membrane responding to gas pressures. The sensitive volume of this sensor is about 0.53 mm^3. The dynamic properties of this model and the required modifications are presented in subsequent paragraphs.

3. Testing the dynamic properties of sensors

As was mentioned earlier, it is not possible to determine the time-constant of pressure sensors used for measuring gas pressure in pores in the same manner as in ideal thermometers for example. The Authors undertook to test the dynamic properties of such sensors and to use them to monitor the rarefaction wave generated in a briquette pipe filled with CO_2 or He up to the pressure $p_{nas} = 0.6$ MPa. The rarefaction wave was generated as in other experiments using coal — i.e. the membrane was suddenly cut (Gawor et al. 1994).

The experimental set-up is shown schematically in Fig. 3. In the side surfaces of the briquette pipe (in the planes indicated I–IV) are locations for pressure transducers and the strain gauges and thermal elements. The distance between the neighbouring planes was 28 mm. In the position indicated as 0 is the piezoresistant pressure-transducer (Siemens) used for measuring the free gas pressure ahead of the briquette front; it was also used for triggering the recording circuit.

Fig. 4 presents the registered pressure changes caused by rapid decompression of the helium filling the whole briquette pipe (without any briquette inside). In positions I and II are sensors (model b), in the position III — sensors, models a and c. Decompression of helium proceeds very rapidly (the velocity of the acoustic wave is about 970 m/s). Registered pressure variations are monotonic, and the compression wave reflected from the piston is not detected. The process of carbon dioxide decompression is depicted in Fig. 5. In this case the process is much slower (velocity of the acoustic wave — about 260 m/s). In enlarged sections of the obtained curves, the moment when the compression wave reflected from the piston would pass may be easily seen.

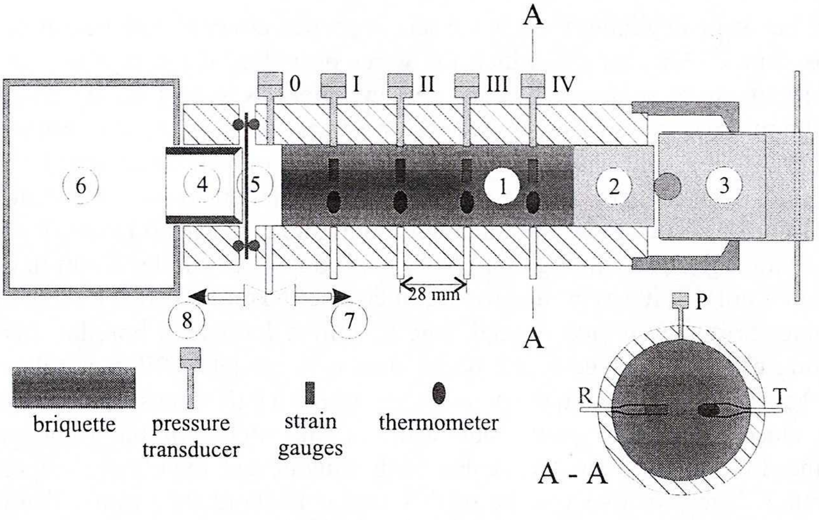

Fig. 3. Experimental set-up
1 — briquette, 2 — piston, 3 — bolt, 4 — knife, 5 — membrane, 6 — decompression pipe, 7 — vacuum pump, 8 — gas bottle

Rys. 3. Schemat stanowiska pomiarowego
1 — brykiet, 2 — tłok, 3 — śruba, 4 — nóż, 5 — membrana, 6 — rura rozprężeniowa, 7 — pompa próżniowa, 8 — butla z gazem

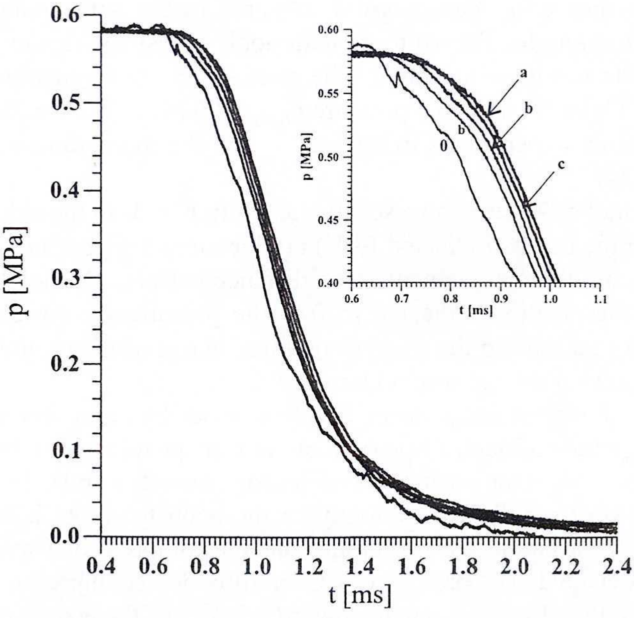

Fig. 4. Pressure variations during the decompression of helium

Rys. 4. Zmiany ciśnienia przy rozprężaniu helu

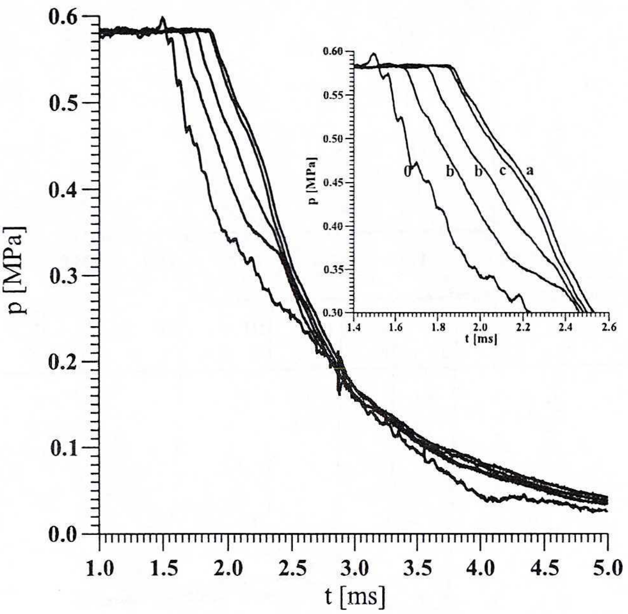

Fig. 5. Pressure variations during the decompression of carbon dioxide

Rys. 5. Zmiany ciśnienia przy rozprężaniu dwutlenku węgla

It can also be seen that the transducers applied to provide the measurements are too slow for the investigation of acoustic waves in helium. They can be useful in the investigation of slower waves, such as those generated in carbon dioxide. All the same, attempts should be made to increase the distance between the sensors so as to prolong the time of wave travel between them. Measurements reveal that sensors thus engineered can be used in the measurement of variable pressures, at frequencies of up to 10 kHz. This opinion is confirmed by the analysis of the frequency spectrum obtained using the Fourier transform.

To check whether such sensors are well suited for measurements of gas pressure in briquette pores, several experiments were conducted involving the outbursts of coal briquettes with 24 % porosity and saturated with helium up to 0.7 MPa. One by one, pressure sensors were fitted in the briquette pipe wall and their readouts were compared with Data Instruments pressure transducers (marked by “a”). The descriptions of recorded pressures, strains and temperatures graphs include: the number of the measurement plane (I–IV); the symbol of the sensor model (a–c) and the sensitive volume (V_m).

Variations of briquette strains ε and of gas pressure registered by two old-type sensors (type a — old models, with the sensitive volume 6 mm^3) and two new sensors (model b) with the sensitive volume 3.3 mm^3, are graphed in Fig. 6. Sensor 0, measuring the free gas pressure ahead of the briquette front, indicates a slight pressure increase due to the shifting of the membrane under the pressure of the knife; that is followed by

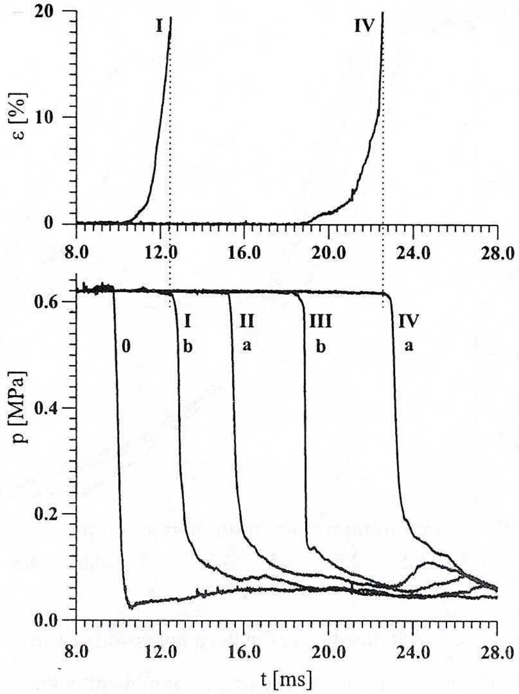

Fig. 6. Time-variations of gas pressure and coal strain variations (V_a = 6 mm^3; V_b = 3.3 mm^3)

Rys. 6. Zmiany w czasie ciśnienia gazu i odkształcenia węgla (V_a = 6 mm^3; V_b = 3,3 mm^3)

a rapid pressure drop as soon as the membrane is cut. Four sensors used for measuring gas pressure near the briquette side surface (i.e. pressure in the briquette pores) behave in a very similar manner. The expected drop of pressure measured by the transducer in position I (model b) in the time interval from 10.4 to 12.6 ms was not recorded. During that period of time the strain gauge in position I was registered the increasing of briquette strain ε up to 20%, followed by the briquette breaking at 12.6 ms. When the briquette begins to break, the pressure readout from the transducer decreases rapidly. Taking into account the strain gauge readouts, one can easily compute that a coal layer decompressing by about 20% will lead to an 1.8 — increase in the pore volume. In accordance with the perfect gas laws, it can be estimated that the gas pressure in the pores at the instant the briquette breaks ought to diminish to about 0.34 MPa. However, the most significant pressure drop before the briquette begins to break is found on the curve (position III) and is as low as 0.03 MPa. These observations lead to one conclusion: the sensitive volume V_m = 3 mm^3 is still too large and the flow of gas from the sensitive volume to the pores within the time interval 2 ms is still too small.

Another pressure transducer was made (model c), where the sensitive volume was 0.53 mm^3. Fig. 7 presents pressure variations registered with four sensors. In position IV is an "old-type" sensor (model a), a "new" sensor (model c) and a strain gauge. From the time-instant 17.6 ms the strain gauge in position IV registers the increasing strain, the briquette breaking at the instant 20.6 ms. Both pressure transducers register a very rapid pressure drop, starting from the instant 20.8 ms. As soon as the briquette breaks, pressure changes registered with these two transducers are nearly identical, while the earlier readouts were entirely different. The sensor (model a) will register a constant pressure p_{nas} until the briquette breaks. The new sensor (model c) registers slight pressure drops starting from the instant 18.4 ms. Afterwards the pressure is stabilised till it begins to increase unexpectedly by about 0.06 MPa at 20.4 ms. The readouts from the two sensors are nearly identical, though the sensitive volume in one of them is 10 times greater. That means that all sensors designed by our team are completely adequate for free gas pressure measurements. Because of the registered, unexpected pressure change prior to the briquette breaking, the new sensor c is viewed with circumspection. The explanation of its behaviour might be facilitated by a closer inspection of Fig. 2c. The membrane responding to external pressures is 1.5 mm in diameter and the distance between the membrane and the briquette side surface is about 0.3 mm. Probably during the crack-formation phase some tiny coal fragment hit the membrane thus producing a signal interpreted as a pressure increase. The likelihood of the membrane being ruptured by coal fragments was circumvented as follows. A metal plate 0.1 mm in

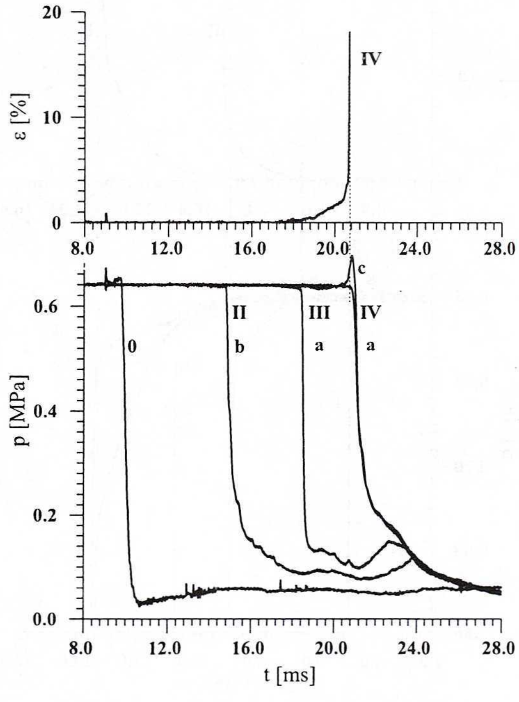

Fig. 7. Time-variations of gas pressure and coal strain variations ($V_a = 6\ \text{mm}^3$; $V_b = 3.3\ \text{mm}^3$; $V_c = 0.53\ \text{mm}^3$)

Rys. 7. Zmiany w czasie ciśnienia gazu i odkształcenia węgla ($V_a = 6\ \text{mm}^3$; $V_b = 3{,}3\ \text{mm}^3$; $V_c = 0{,}53\ \text{mm}^3$)

thickness was glued to the concave front surface of the transducer body. In this metal plate are 6 holes 0.3 mm in diameter, closely spaced. This transducer was again fitted in position IV, next to the model a transducer. In positions II and III were two identical model c sensors. The sensitive volume in these sensors was about 0.2 mm^3. However, because of some errors in construction, the contact pressure between the sensor front section and the briquette surface could not be precisely controlled. When there is a gap between these surfaces, results of pressure measurements may include some errors. This drawback can be easily removed though it is a time-consuming operation. The results of this experiment are presented in Fig. 8. In order to present the initial variations of

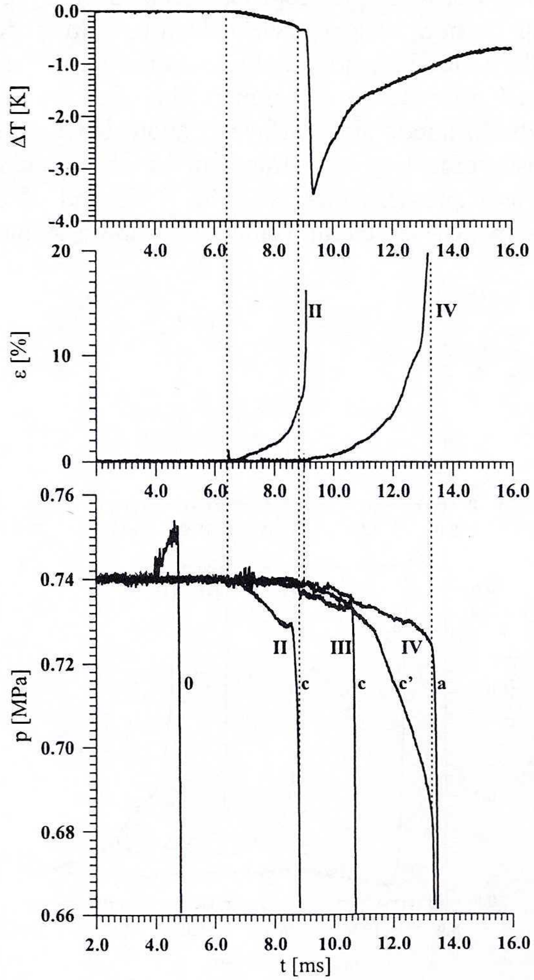

Fig. 8. Time-variations of temperature, strain and gas pressure ($V_a = 6$ mm^3; $V_{c'} = 0.53$ mm^3; $V_c = 0.20$ mm^3)

Rys. 8. Zmiany w czasie temperatury, odkształcenia i ciśnienia gazu ($V_a = 6$ mm^3; $V_{c'} = 0{,}53$ mm^3; $V_c = 0{,}20$ mm^3)

pressure, strain and temperature, the range of their values was restricted (the pressure axis range is 0.66 to 0.76 MPa, for strains the range is 0–0.2). This diagram clearly illustrates the interrelations between the initial responses of individual sensors to the changes in measured quantities (vertical, broken lines).

A thermal element, a strain gauge and a pressure gauge in position II began to register the changes in the measured parameter at 6.4 ms. The instant the briquette breaks along that plane, as manifested by rapid changes in the measured quantity, is actually the same. In position II and III pressure decreases by nearly 0.02 MPa, then decreases rapidly. The moment marking the beginning of pressure changes was registered by two sensors in position IV and the beginning of the expansion of the briquette will also be coincident in time. Immediately before the briquette begins to break, the pressure readout from the model a transducer is lower by about 0.015 MPa and that read from the modified transducer c — by 0.06 MPa. From the instant the crack appears (i.e. when the briquette breaks), the readouts from these two sensors are the same. During the stage of briquette decompression, the strain slowly increases at first, then it begins to grow rapidly. The same pattern can be observed on the curve c' which represents the change of gas pressure. The pressure variation pattern registered with the sensor c' suggests that the sensor were positioned sufficiently close to the briquette structure with the membrane smaller than 1 mm, the measured values would be much closer to the real.

Conclusions

An appreciable reduction of the sensitive volume in sensors allows the time variations of gas pressure in pores during the stage of briquette decompression to be monitored; that is about 2 ms before a crack should appear. A sensor with the sensitive volume of less than 0.5 mm^3 registers very distinct pressure changes throughout this time interval. Measured pressures are probably higher than the real pressures in the pores.

The real gas pressure changes in the pores can be more exactly reproduced using miniature pressure transducers where the membrane dimensions are of the order of the tenth of a millimetre.

Measurements of gas pressure in cracks, following the briquette breaking, can be taken with pressure sensors with a sensitive volume of up to several cubic millimetres.

It is not possible, therefore, to verify or reject the hypothesis which states that rock and gas outbursts are initiated by rarefaction shock waves without extremely precise measurements of gas pressures in the pores taken at moment the briquette disintegrates.

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REVIEW BY: PROF. DR HAB. INŻ. ANDRZEJ SMOLARSKI, KRAKÓW

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