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# ON TURBULENT DIFFUSION COEFFICIENT CONCERNING FLOW OF AIR AND GAS IN MINE WORKINGS

# O WSPÓŁCZYNNIKU DYFUZJI TURBULENTNEJ DOTYCZĄCEJ PRZEPŁYWU POWIETRZA I GAZU W WYROBISKACH GÓRNICZYCH

The article presents the experiments of gas disturbances propagation in a mine ventilation network. The main purpose of the investigation was estimation of a turbulent diffusion coefficient. Calculations were made for measuring signals recorded during the propagation of methane, carbon monoxide and smoke concentration disturbances in mine workings. Disturbances of methane caused by changes in ventilation conditions after auxiliary fan switching-off and shooting in longwall were treated as natural gas markers recorded in the different points of mines along ventilation paths. The turbulent diffusion coefficient was also calculated for smoke signals recorded during burning experiments in experimental workings and for carbon monoxide concentration signals recorded after shooting in mine workings. The diffusion coefficient was calculated using the various methods and comparing the obtained results.

**Key words:** air flow, mine experiments, diffusion coefficient, evaluation, simulation, modeling ventilation process.

Powstające w wyrobiskach kopalni zaburzenia wywołane uaktywnieniem się źródeł domieszek gazowych rozprzestrzeniają się drogami wentylacyjnymi, stopniowo zanikając w miarę oddalania się od ich źródła. Czas i zasięg rozprzestrzeniania się zaburzeń zależy od charakterystyki źródła i warunków przewietrzania. Efekty zaburzeń stężenia metanu w rejonach ścian są obserwowane na przestrzeni wielu kilometrów, a czas ich pojawiania się, określony opóźnieniem transportowym, przekracza nawet kilka godzin. Prędkość rozprzestrzeniania się zaburzeń, związana ze zjawiskiem unoszenia, może być wyznaczana eksperymentalnie, np. metodą funkcji korelacji wzajemnej (Wasilewski, 1997). Zanikanie impulsu w miarę przemieszczania się wzdłuż wyrobiska jest związane ze zjawiskiem dyfuzji.

Zagadnienie rozprzestrzeniania się domieszek gazów w wyrobiskach górniczych było przedmiotem licznych prac, badań laboratoryjnych i eksperymentów kopalnianych (Klebanow, 1974), (Ryncarz, 1969), (Trutwin, 1973). Ich autorzy traktują przepływ w wyrobisku jako jednowymiarowy, a do opisu zjawiska propagacji gazów przyjmują równanie

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ciągłości w postaci równania różniczkowego cząstkowego typu parabolicznego zwanego powszechnie równaniem dyfuzji:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} + q_m \,. \tag{1}$$

Przepływ powietrza w wyrobisku górniczym charakteryzuje się turbulencją wyrażoną (1) przez współczynnik dyfuzji turbulentnej $D$. Zagadnienie oszacowania współczynnika dyfuzji było przedmiotem licznych prac (Gumuła, et al., 1973), (Jarembasz, 1970), (Klebanow, 1974), (Szlązak, 1996). W większości z nich autorzy wykazują zależność tego współczynnika od prędkości przepływu. Takie wyniki otrzymał m.in. Jarembasz (1970), który badania opierał na analizie wymiarowej. Również badania laboratoryjne (Gumuła, et al., 1973) oraz prowadzone w warunkach kopalnianych (Klebanow, 1974), (Ryncarz, 1969), (Szlązak, 1996) (Wasilewski, Szywacz, 1989) i (Wasilewski, 1998) potwierdziły zależność współczynnika dyfuzji od prędkości przepływu.

W artykule przedstawiono badania propagacji zakłóceń gazowych w sieci wentylacyjnej kopalni w celu obliczeń współczynnika dyfuzji turbulentnej. Obliczenia wykonano dla sygnałów zarejestrowanych w czasie rozprzestrzeniania się zaburzeń stężenia metanu, tlenku węgla i dymu w wyrobiskach kopalnianych. Zaburzenia, wywołane usuwaniem nagromadzeń metanu wywołanych zmianą warunków przewietrzania, np. wyłączenie wentylatora lutniowego i strzelanie w ścianie, traktowano jako naturalne znaczniki gazowe rejestrowane w różnych punktach kopalń wzdłuż dróg wentylacyjnych. Współczynnik dyfuzji turbulentnej obliczono również dla sygnałów dymu rejestrowanych w czasie eksperymentów spalania prowadzonych w sztolni oraz dla sygnałów stężenia tlenku węgla rejestrowanych w wyrobiskach kopalnianych po strzelaniach wstrząsowych.

Badania propagacji domieszek gazowych wzdłuż wyrobisk kopalnianych przy zmiennych warunkach przewietrzania dostarczyły znaczną ilość danych pomiarowych, które wykorzystano do oszacowania współczynnika dyfuzji różnymi metodami, porównując uzyskane wyniki.

Dane pomiarowe zarejestrowane w czasie obserwacji rozprzestrzeniania się zaburzeń gazu w wyrobisku $\{C_i, x_i, t_i\}$ wykorzystano także do oszacowania współczynnika dyfuzji turbulentnej metodą symulacji cyfrowej tego zjawiska. W tym celu dobór współczynnika dyfuzji uzyskano zmieniając jego wartość tak długo, aż uzyskano najlepsze w sensie błędu średniokwadratowego przybliżenie modelowego rozkładu stężenia z rozkładem rzeczywistym zarejestrowanym za pomocą czujników w danych punktach.

Oszacowane na podstawie rejestrowanych sygnałów wartości współczynnika dyfuzji były wyższe niż obliczone z parametrów wyrobiska oraz prędkości powietrza, np. metodą Jarembasza (1970). W wyrobiskach rzeczywistej kopalni występuje wiele czynników (przeszkód, nierównomierności przekroju, załamań), które mogą znacznie zwiększyć rozproszenie domieszki w płynącym powietrzu. Jest to szczególnie widoczne w przypadku rozprzestrzeniania się zaburzeń metanu w wyrobiskach typu ścianowego. Dla chodników w sztolni CSRG, o gładkich powierzchniach i jednolitych przekrojach, różnice w obliczonych wartościach współczynnika dyfuzji dla sygnałów dymu były niewielkie.

Na podstawie oszacowań współczynnika dyfuzji dla zarejestrowanych sygnałów stwierdzono m. in.:

- długość impulsu zaburzenia gazowego (po strzelaniu) jest proporcjonalna do pierwiastka odległości od źródła zaburzenia;
- współczynnik dyfuzji rośnie ze wzrostem prędkości powietrza;
- współczynnik dyfuzji zależy silnie od nierównomierności przekroju i może osiągnąć znaczne wartości w przypadku występowania przeszkód w przekroju wyrobiska lub załamań wyrobiska, stąd w warunkach kopalni może być wyznaczony jedynie eksperymentalnie.

Zastosowany model zjawiska rozprzestrzeniania się zaburzeń gazu pozwala na dobór współczynnika dyfuzji metodami symulacji komputerowej niezależnie od charakteru zaburzenia. Generowane z modelu rozkłady czasoprzestrzenne stężenia gazu dla współczynnika dyfuzji dobranego metodą symulacji są zgodne z rzeczywistymi. Dobór wartości współczynnika dyfuzji turbulentnej metodą symulacji komputerowej (Wasilewski, Szywacz, 1989) czasoprzestrzennego rozchodzenia się zaburzeń na podstawie aproksymacji wartości pomiarowych stężenia gazu w wyrobisku kopalnianym, okazał się skutecznym sposobem oszacowania tego parametru.

**Słowa kluczowe:** przepływ powietrza, eksperymenty kopalniane, współczynnik dyfuzji, oszacowanie, symulacja, modelowanie procesów wentylacji.

## 1. Introduction

The problem of gas disturbances propagation in mine workings was a subject to many studies, laboratory tests and mine experiments. Their authors accepted equation of continuity in a form of parabolic type, commonly called a diffusion equation (Klebanow, 1974), (Ryncarz, 1969), (Thakur, 1975) for the description of gas propagation. The problems of solving differential equations describing the phenomena of gas flow and propagation for various boundaries — initial conditions were studied at Strata Mechanics Institute of the Polish Academy of Science in Kraków (Czyczuła, 1973), (Gumuła et al., 1973), (Kruszyński, 1973), (Trutwin, 1973).

The turbulence of airflow in mine working is expressed by turbulent diffusion coefficient. The evaluation of diffusion coefficient has shown its dependence on airflow velocity (Gumuła et al., 1973), (Klebabow, 1974), (Lee, 1995), (Ryncarz, 1969), (Thakur, 1975). Such results were obtained also by Jarembasz dimensional analysis (Jarembasz, 1970) and laboratory tests and mine experiments (Klebanow, 1974), (Ryncarz, 1969), (Szlęzak, 1996), (Wasilewski & Szywacz, 1989), (Wasilewski, 1998) confirming the dependence of diffusion coefficient upon airflow velocity.

The tests (Wasilewski & Szywacz, 1989), (Wasilewski & Szywacz, 1989) on propagation of methane disturbances along mine workings as a result of ventilation conditions, delivered a great number of measuring changeable data. They were used for evaluation of diffusion coefficient by various methods. Similar calculation was done for the smoke concentration signals recorded during experimental burning (Wasilewski, 1997) and the signals of carbon monoxide after — shooting concentration were also used.

## 2. The methods for diffusion coefficient determination

Space-time distribution of gas admixtures concentration in the air flowing through duct which is much longer than diameter, can be approximately described by differential partial equation of parabolic type commonly called as diffusion equation:

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} - v\frac{\partial C(x,t)}{\partial x} + q_m \tag{1}$$

where:

$C(x,t)$ — gas concentration in air,
$D$ — turbulent diffusion coefficient,
$q_m$ — expenditure of gas source,
$v$ — air flow velocity,
$x$ — co-ordinate along working axle,
$t$ — time.

### 2.1. Assumptions of Taylor's theory

The test results of gas admixture propagation in turbulent flows in straight pipes have been presented by Taylor who came to the following conclusions:

1. Admixture propagation in turbulent flow of medium flowing through a straight pipe is described by effective diffusion coefficient:

$$K = 10.1\, a v^{*}$$

where $a$ is a hydraulic diameter of pipe and $v^{*}$ is a dynamical velocity equal to:

$$v^{*} = v\sqrt{\varphi/2}$$

while $v$ is an average velocity of medium in pipe and $\phi$ is Chézy-Darcy coefficient. These formulas are correct for both the smooth and rough surface of pipes.

2. Propagation of gas admixtures at a set boundary and initial values in a form of admixture impulse ($x = 0,\ t = 0$) is described by Gauss's curve:

$$C(t) = A t^{\frac{-1}{2}} \exp\left[\frac{-(x - vt)^{2}}{4Kt}\right]$$

where a constant $A$ is dependent on the total quality of a diffusing admixture. This curve makes a solution of diffusion equation (1).

3. Maximum concentration of admixture impulse moves on with an average velocity of admixture flow.

4. Passing time of admixture impulse through a point in a distance from source defined as time at which concentration in this point exceeds a half of the maximum value, is inversely proportional to average velocity of a stream. However, a product of passing time by average velocity does not depend on this velocity. This product has been called an impulse length (it has size of distance [m]) and its value is proportional to square root from the distance between the observation point and admixture source.

5. The value of effective diffusion coefficient can be determined experimentally from the relation:

$$K = \frac{v^{3}\tau_{1/2}^{2}}{4x\ln 2},$$

where $2\tau_{1/2}^2$ is an impulse passing time through a given point and $x$ is a distance between the observation point and point of the admixture source.

The experimental verification of the assumptions of Taylor's theory under mining conditions, undertaken by Hodkinson and Leach (Klebanow, 1974) has proved Taylor's theory. Besides, the authors have noticed that:

1. maximum admixture concentration is approximately inversely proportional to the distance from source,
2. impulse duration is a constant for a given distance from source at any air flow velocity.

### 2.2. The method of dimensional analysis — Jarembasz's relation

Dependence of the diffusion coefficient upon geometrical parameters of a working and average velocity was defined by dimensional analysis by Jarembasz (1970).

For mine workings of up to 1000 m depth for which air density and kinematics viscosity coefficient have been accepted as constant and equal $\varrho = 1.2$ kg/m$^3$, $v = 15$ $10^{-6}$ m$^2$/s Jarembasz (1970) has given the following dependence of diffusion coefficient:

$$D = 12\sqrt[3]{\alpha S v^2} \tag{2}$$

where: $\alpha$ is resistance coefficient [kg/m$^3$] defined from the relation

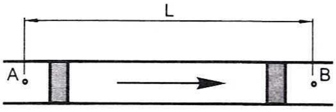
$$\alpha = \frac{\lambda \varrho}{8},$$

where $\lambda$ is dimensionless resistance coefficient and $\varrho$ is air density [kg/m$^3$], $s$ is area cross-section [m$^3$] and $v$ is air velocity in working [m/s].

Relation in this form was verified by Jarembasz in a way of mine experiments.

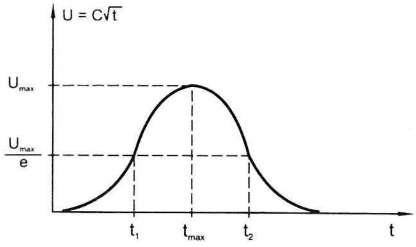
### 2.3. The method of approximation by Klebanov's function

Suppose to the beginning section $A$ (point of the source Fig. 1a) of a working, gas admixture is introduced. Patch together with air will move towards observation point $B$. During flowing gas patch will diffuse. The diffusion degree depends on the average air flow velocity (Klebanow, 1974), distance between points $A$ and $B$, and turbulent diffusion coefficient which in addition depends on the walls roughness section irregularity cross-section and curvature of a working. Creating a curve $U(t) = C\sqrt{t}$ (Fig. 1b) for measuring data in point $B$ and defining its intersection points ($t_1$ and $t_2$) with straight line $U(t) = \max(C\sqrt{t})/e$ the value of turbulent diffusion coefficient is determined from the relation



Propagation of gas admixtures in a working

Fig. 1a. Scheme of gas admixtures propagation in a mine working



Graph of function U(t) = C√t

Fig. 1b. Graph of function $U(t) = C$ for determination of turbulent diffusion coefficient value

$$K = \frac{v^2 (\sqrt{t_2} - \sqrt{t_1})^2}{4}, \tag{3}$$

where $v$ is an average air flow velocity in working.

### 2.4. The method basing on observation of waves propagation

Making (Gumuła et al., 1973) use of the diffusion equation (1) and basing on the observation of changes in space-time distribution of concentration, and on the measurement, at the same time, of air flow velocity and intensity of methane source, the diffusion coefficients for each points $(x, t)$ have been determined from relation

$$D = \frac{\dfrac{\partial C}{\partial t} + v \dfrac{\partial C}{\partial x}}{\dfrac{\partial^2 C}{\partial^2 x}}. \tag{4}$$

The approximation of partial derivatives determined on the basis of measurements in the following form, are accepted for calculation:

$$\frac{\partial c}{\partial x} = \frac{C(x_{i+1}, t) - C(x_i, t)}{\Delta x} \tag{5}$$

$$\frac{\partial^2 C}{\partial x^2} = \frac{C(x_{i+1}, t) - 2C(x_i, t) + C(x_{i-1}, t)}{(\Delta x)^2} \tag{6}$$

$$\frac{\partial C}{\partial t} = \frac{C(x, t_{k+1}) - C(x, t_k)}{\Delta t} \tag{7}$$

where $\Delta x$ is a distance between the points of wave recording and $x_1$ co-ordinate of iterated measuring point $x_1 = i\Delta x$, and $\Delta t$ is sampling time.

By evaluating a diffusion coefficient for each moment of time $t_k = t_0 + k\Delta t$ the instantaneous coefficients $D_k$ have been obtained; they being averaged after time:

$$D = \frac{1}{k_t} \sum_{k=1}^{k_1} D_k \tag{8}$$

have been accepted as evaluation of turbulent diffusion coefficient.

## 2.5. Estimation diffusion coefficient by a digital simulation method

The measuring data recorded during observation of gas disturbances propagation in a working $\{C_i, x_i, t_i\}$ were used (Wasilewski, Szywacz, 1989) for digital simulation. The diffusion equation (1) was solved under the following boundary — initial conditions:

$$C(x, 0) = 0$$
$$C(0, t) = S(t)$$

and equation of space-time distribution of gas concentration in working was obtained:

$$C(x, t) = \frac{x e^{\frac{v}{2d} x - \frac{v^2}{4d} t}}{2\sqrt{\pi d}} \int_0^t \frac{e^{\frac{x^2}{4d(t-\tau)}} e^{\frac{v^2}{4d^{\tau t}}} S(\tau)}{(t-\tau)\sqrt{t-\tau}} d\tau . \tag{9}$$

The digital simulation of space — time distribution of methane concentration in working was performed on the base of numerical form of this model. For approximation of boundary concentration $S(t)$, function $S(t)$ was used in a form of

$$S(t) = a t^b e^{-ct}, \tag{10}$$

the coefficients of which were determined on the basis of methane concentration changes on entry to working. Utilising model equations one can determine by a digital simulation method, the space — time distribution of gas concentration in sections $x_i$ where it has been recorded.

Choice of diffusion coefficient is made by changing the coefficient as long as the optimal value, as a mean — square error, approximation of model concentration distribution and real data recorded by sensors will be found.

Mean square error is calculated from relation

$$\varepsilon(\mathrm{D}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[x_i - y_i(D)\right]^2}$$

where $x_i = 1, \dots N$ are real values of gas concentration recorded at the moments $i = 1, \dots N$, and $y_i$ are the values calculated from a model.

## 3. Tests on disturbances propagation in network

To compare the different methods for diffusion coefficients estimation, the gas admixtures propagation, was recorded in the mine workings (Wasilewski, Szywacz, 1989), (Wasilewski 1998).

### 3.1. Observation on methane disturbances propagation

Measuring data were recorded for three kinds of disturbances (Wasilewski, Szywacz, 1989):

- removal of methane accumulation from longwall,
- removal of methane accumulation after stopping and starting auxiliary fan,
- removal of methane after shooting.

In each case, methane wave propagation was controlled by sensors placed along ventilation path in outlet currents of used air from the test area.

*Removal of methane accumulation after ventilation disturbances at the longwall area*

Observations were made in the area of longwalls 613 and 614 in bed 405 at depth of 720 m at STASZIC mine. To disturb the methane concentration in outlet currents,

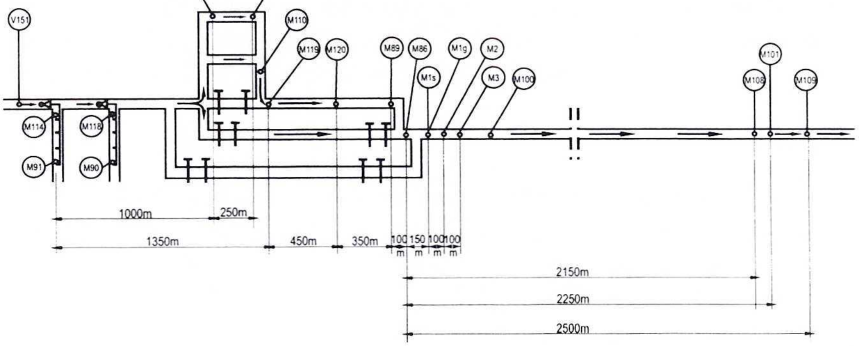
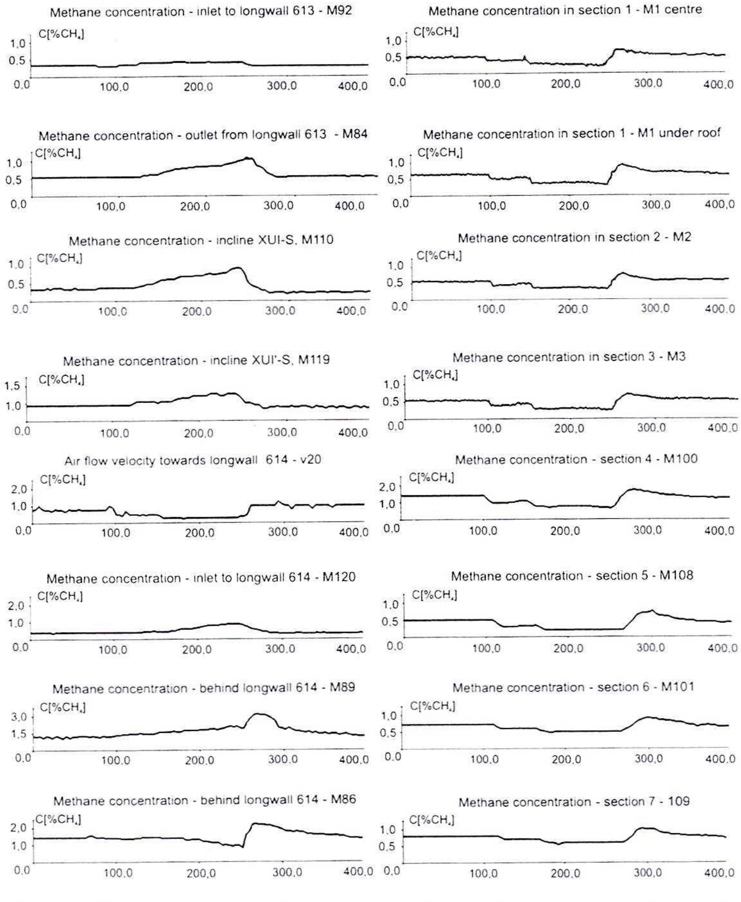


Fig. 2. Location of measuring points along propagation path of methane disturbances in the area of longwall 613 and 614

an experiment was carried out. It consisted in a disturbance of ventilation conditions by short — circuit.

Methane propagation was recorded by the sensors the location of which is shown in Fig. 2. The experiment run and obtained effects have been discussed [14]. Due to air discharge reduction at longwall area, the increase in methane concentration at longwall and its outlet followed. After restoring primary ventilation conditions, accumulated methane was pushed out to incline drift *S*. The wave of methane concentration disturbances was recorded by sensors placed at measuring point (Fig. 3). Transport delay for the most distant point (about 4 km) was about 50 minutes.


Methane concentration - inlet to longwall 613 - M92

Methane concentration in section 1 - M1 centre

Methane concentration - outlet from longwall 613 - M84

Methane concentration in section 1 - M1 under roof

Methane concentration - incline XUI-S, M110

Methane concentration in section 2 - M2

Methane concentration - incline XUI'-S, M119

Methane concentration in section 3 - M3

Air flow velocity towards longwall 614 - v20

Methane concentration - section 4 - M100

Methane concentration - inlet to longwall 614 - M120

Methane concentration - section 5 - M108

Methane concentration - behind longwall 614 - M89

Methane concentration - section 6 - M101

Methane concentration - behind longwall 614 - M86

Methane concentration - section 7 - 109

Fig. 3. Propagation of methane disturbances after methane accumulation at longwall 614

*Removal of methane accumulation by restarting auxiliary fan*

In the area there were two development headings ventilated by auxiliary fan with ventilation pipes pumping fresh air to mine faces. In order to obtain methane accumulation, two fans were stopped for about 3 hours. This caused an increase in methane concentration at the mine faces up to 3% of $CH_4$ (sensors M490 and

M491). Methane concentration at the exit face also increased (M114 and M118). After fans switching — on, methane disturbances accumulation was pushed out to ventilation paths and was flowing together with air. This effect was recorded by the sensors installed along ventilation paths in the area (Fig. 4).

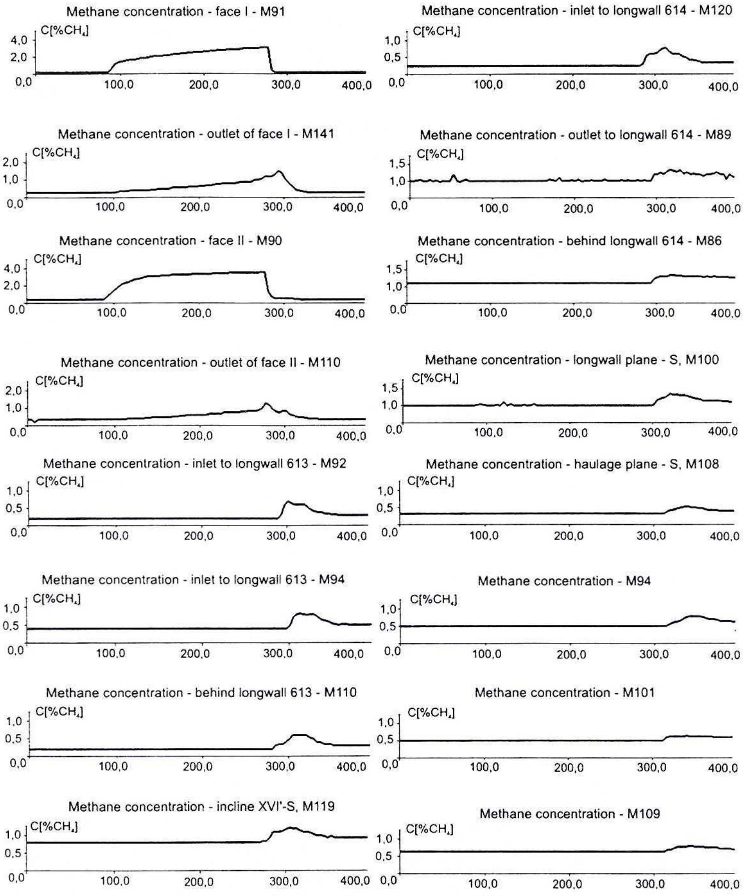


Fig. 4. Propagations of methane disturbances after stopping and restarting fans at mine faces

## *Methane removal after shooting*

The propagation of methane concentration disturbances along mine workings after shooting at mine faces is related to removal of after — damp gases. This goes

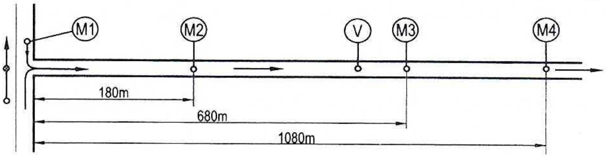


Fig. 5. Location of measuring points during observation on methane disturbances propagation after shooting

together with rapid changes in methane concentration especially close by a source (mine face). To analyse this effect, the measuring data recorded in the area of longwall F-7 at "ZOFIOWKA" colliery were used. A scheme of ventilation system for longwall F-7 with sensors location is shown in Fig. 5. The observations on methane concentration disturbances diffusing along ventilation path after shooting at mine face, are shown in figure 6.

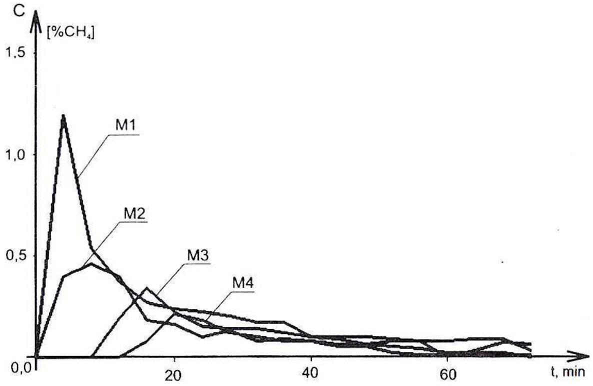


Fig. 6. Propagations of methane disturbances after shooting at mine face

### 3.2. Observations on smoke propagation during experimental burning

The experiments were conducted in workings at the Central Mining Rescue Station in Bytom. They consisted in burning the different portions of wood and observations on smoke propagation in workings. The scheme of workings and sensors are shown in Fig. 7. Workings had a rectangular section and were as a whole made of concrete. Air discharge in workings was controlled by a fan and air stoppings. During the experiments, wood portions of 1 kg, 5 kg and 10 kg were burned, while air quantity was respectively $4\,m^3/s$, $12\,m^3/s$ and $24\,m^3/s$.

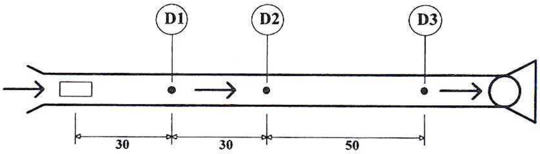


Fig. 7. Location of smoke measuring points diving experimental burnings

The smoke propagation effect was recorded by three smoke detectors type ADD-1, placed at a distance of 30, 60 and 110 m from the fire. Propagation of smoke disturbances during the experiments are shown in Fig. 8.

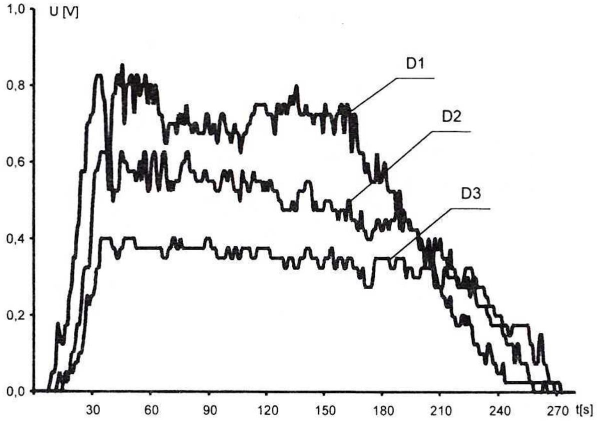


Fig. 8. Propagation of smoke disturbances during experimental burning

## 3.3. Observations on the propagation of carbon monoxide concentration disturbances after shock shooting

To observe propagation of carbon monoxide concentration disturbances after shock shooting at "MIECHOWICE" colliery, the SAP-1 fire monitoring system was used. The system sensors were installed at longwalls 92 and 93 in bed 509, on level of 720 m. The bed ranked (high tendency) with III group of self-ignition, III class of methane hazard and class B of dust hazard. Besides the bed was exposed to bounce danger, so shock shooting was there preventively conducted. The scheme of experiments area and location of sensors are shown in Fig. 9. During experiments and normal operation many observations were made in this area. Fire monitoring system recorded CO signals in working after shock shooting in stone, when cross-heading 64 was driven, and also after shooting at longwalls. Fig. 10 shows the disturbances of carbon monoxide concentration after a shooting.

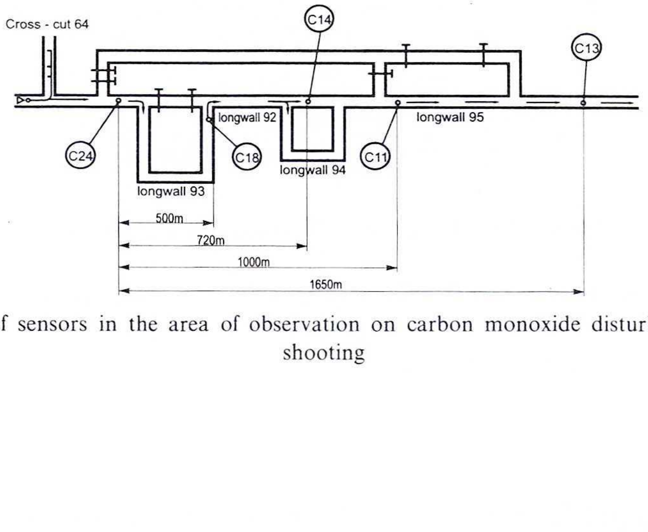


Fig. 9. Location of sensors in the area of observation on carbon monoxide disturbances after shock shooting

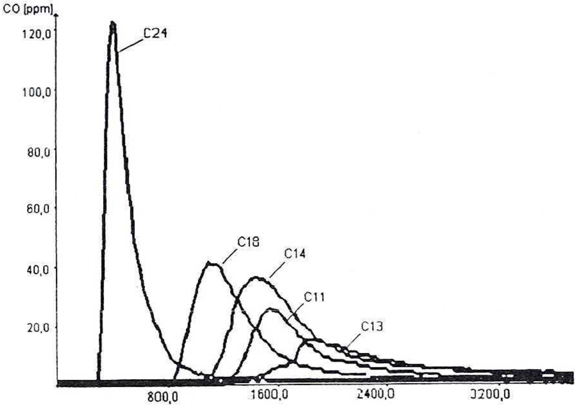


Fig. 10. Propagation of carbon monoxide after shock shooting

## 4. Estimation of average velocity of gas disturbances propagation in ventilation system

Average velocity of air flow in working (Gumuła et al., 1973), (Klebanow, 1974), (Lee, 1995), (Szlązak, 1996) makes the most important parameter necessary for the estimation of a diffusion coefficient. Observations on the signals recorded at the mine have shown that local air flow velocity not always corresponds with the values determined by delays of gas disturbances propagation. This concerns, first of all, the measuring points being far away from each other. Verification of the measured air flow velocities was made by their comparison with the velocities defined by an correlation method (Wasilewski, 1998).

In case of propagation of the methane and carbon monoxide concentration disturbances, the average air flow velocities were evaluated by correlation method, among other for:

- 2 km long haulage inclined drift *S*, during removal of methane accumulation after experiment in the lingual area,
- longwalls 613 ($v = 0.25$ m/s) and 614 ($v = 0.35$ m/s) the velocities for which, defined in such a way, can be recognised as most reliable,
- area of longwall F-7 during removal of methane wave after shooting, $v = 1.02$ m/s.

## 5. Evaluation of diffusion coefficient based on measuring data

### 5.1. Evaluation of diffusion coefficient for methane concentration signals

A diffusion coefficient for two parts of haulage inclined drift *S* was calculated on the basis of data recorded by sensors M1, M2, M3 and M108, M101, M109 during experiment related to removal of methane accumulation.

After elimination of background and runs approximation by function $S(t)$, to smooth the fluctuations of instantaneous values, a diffusion coefficient for the front of methane wave signal was calculated (table 1).

TABLE 1

The results of diffusion coefficient evaluation for the data at the longwall area

| | | Approximation $S(t)$ | | | | | |
|---|---|---|---|---|---|---|---|
| | Distance [m] | $a$ | $b$ | $c$ | $D_J$ | $D_F$ | $D_S$ |
| M1 | 150 | 0.07160 | 0.965 | 0.0350 | | | |
| M2 | 250 | 0.02400 | 1.389 | 0.0600 | 7.637 | 5.74 | 16.33 |
| M3 | 350 | 0.01500 | 1.641 | 0.0780 | | | |
| M1 08 | 2120 | 0.00073 | 2.490 | 0.0695 | | | |
| M1 01 | 2250 | 0.00020 | 2.460 | 0.0396 | 8.667 | 63.79 | 71.32 |
| M1 09 | 2500 | 0.00016 | 2.450 | 0.0310 | | | |

where:

$D_J$ — diffusion coefficient evaluated from Jarembasz's relation (2),

$D_F$ — diffusion coefficient evaluated by wave observation method from diffusion equation (4),

$D_S$ — diffusion coefficient selected on the basis of simulation model (9).

The results of diffusion coefficient evaluation (table 1), show that the evaluation results near a source are similar but in case of remarkable distance they distinctly differ. In particular this concerns Jarembasz's method which disregards the relation between diffusion coefficient and distance (Fig. 11).

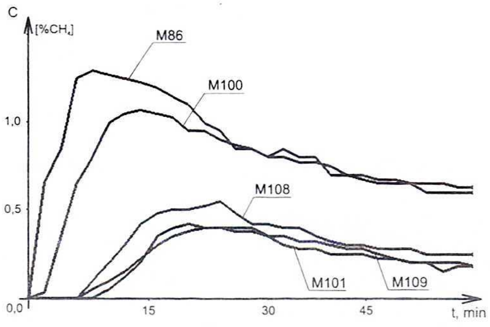


Fig. 11. Distributions of methane concentration for evaluated diffusion coefficient, generated from simulation model

Use of measuring data resulted from methane wave displacement after stopping and restarting of fans, enabled to determine a diffusion coefficient for longwalls 613 and 614 (table 2).

TABLE 2

The results of diffusion coefficient evaluation for data after stopping and restarting fans

| | | | | | Approximation $S(t)$ | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Distance [m] | $V_{śr}$ m/s | $a$ | $b$ | $c$ | $D_J$ | $D_S$ |
| longwall | inlet | M92 | 1000 | | 0.010700 | 2.50 | 0.1939 | | |
| 613 | | | | 0.25 | | | | 3.19 | 63.49 |
| | outlet | M84 | 1250 | | 0.000397 | 2.52 | 0.0387 | | |
| longwall | | M119 | 1350 | | 0.01570 | 1.265 | 0.0357 | | |
| 614 | inlet | M120 | 1800 | 0.35 | 0.00235 | 1.812 | 0.0319 | 4.46 | 37.17 |
| | outlet | M89 | 2050 | | 0.00130 | 1.750 | 0.0316 | | |

Similar to the previous in table 2, $D_J$ means diffusion coefficient evaluated by Jarembasz's method relation (2), and $D_S$ one is selected by digital simulation method model (9). For evaluation the mean air flow velocities in longwall calculated by correlation method, were used. As it results from calculation, the diffusion coefficient $D_S$ for longwalls is much greater than $D_J$ one. These results have confirmed that Jarembasz's relation disregards a specific character of workings, longwall type with very irregular sections and many obstacles.

TABLE 3

Parameters of methane impulse after shooting

| | | | | Approximation $S(t)$ | | |
|---|---|---|---|---|---|---|
| No of shooting | | Distance [m] | $V_{śr}$ [m/s] | $A$ | $b$ | $C$ |
| | M1 | — | | $2.00 * 10^{-5}$ | 8.585 | 0.9997 |
| | M2 | 180 | | $6.00 * 10^{-6}$ | 9.151 | 0.8490 |
| 56 | M3 | 680 | 1.04 | $6.13 * 10^{-9}$ | 8.698 | 0.4200 |
| | M4 | 1080 | | $5.94 * 10^{-10}$ | 8.639 | 0.3330 |
| | M1 | — | | $2.19 * 10^{-6}$ | 11.565 | 1.332 |
| | M2 | 180 | | $5.32 * 10^{-5}$ | 7.408 | 0.753 |
| 70 | M3 | 680 | 1.12 | $2.13 * 10^{-8}$ | 8.610 | 0.475 |
| | M4 | 1080 | | $1.22 * 10^{-9}$ | 8.660 | 0.360 |

Measuring data recorded during methane wave displacement after shooting had a character of passing impulse (table 3). This allowed to calculate diffusion coefficient by Klebanow's method, and also to verify some assumptions of Taylor's theory (table 4).

TABLE 4

The result of diffusion coefficient evaluation for data after shooting

| No | Parameters | | | | | | | | | $D_J$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Taylor | | | | | | Klebanow | | | |
| | | $C_{max}$ | $T_{max}$ | $\tau_{1/2}$ | $L$ | $L/\sqrt{x}$ | $t_1$ | $t_2$ | $D_K$ | |
| 56 | M1 | 1.10 | 6.31 | 2.13 | 147.4 | — | 5.5 | 14.0 | 24.8 | 4.673 |
| | M2 | 0.60 | 10.78 | 4.22 | 252.7 | 37.68 | 6.9 | 17.4 | 35.1 | 9.284 |
| | M3 | 0.29 | 20.71 | 8.30 | 498.3 | 38.22 | 7.5 | 19.2 | 71.0 | 4.885 |
| | M4 | 0.17 | 25.92 | 10.43 | 625.7 | 38.08 | 8.3 | 21.5 | 89.5 | 5.081 |
| 57 | M1 | 1.00 | 5.71 | 2.37 | 150.3 | — | 5.6 | 15.4 | 22.4 | 4.878 |
| | M2 | 0.73 | 9.84 | 4.22 | 256.6 | 38.25 | 6.0 | 16.7 | 39.6 | 9.692 |
| | M3 | 0.27 | 18.13 | 7.31 | 438.6 | 33.63 | 8.9 | 22.2 | 62.8 | 5.100 |
| | M4 | 0.19 | 24.06 | 9.71 | 580.5 | 35.30 | 10.1 | 27.6 | 82.8 | 5.304 |

Shown in table 4, the parameters according to Taylor stand for:
$C_{max}$ — maximum value of impulse ($CH_4$%),
$T_{max}$ — time of maximum occurrence (minutes),
$\tau_{1/2}$ — passage time (minutes),
$L$ — impulse length (meters),
$L/\sqrt{x}$— proportionality coefficient,
$t_1$, $t_2$ — times read — out from Klebanow's function $U = C\sqrt{t}$,
$D_K$ — diffusion coefficient determined from Klebanow's function (3),
$D_J$ — diffusion coefficient calculated by Jarembasz's method (2).

The results shown in table 4 confirm a postulate of Taylor's theory that impulse length is proportional to distance root (this coefficient figures 38). The values of diffusion coefficients evaluated from Klebabow's function $D_K$ show distinct repeatability. Instead, the great differences of these coefficients in relation to those calculated by Jarembasz's method, confirm that latter disregards real conditions of the mine (for example obstacles in working section) and owing to this underrate the calculated diffusion coefficients.

## 5.2. Evaluation of diffusion coefficients for smoke signals

Measuring data recorded during experimental burning enabled to estimate the values of coefficient for various air flow velocities. Tests were conducted in a drift of the Central Mining Rescue Station. Experimental burning was made for three different air velocities 0.5 m/s, 1.5 m/s and 3 m/s. The results of diffusion coefficient evaluation are shown in table 5.

TABLE 5

Diffusion coefficient values for smoke signals

| No of experiment | $V$ m/s | $D_J$ | $D_F$ | $D_S$ |
|---|---|---|---|---|
| 6 | 0.5 | 2.98 | 3.9 | 6.48 |
| 3 | 1.5 | 6.197 | 10.23 | 11.2 |
| 4 | 3.0 | 9.84 | 17.76 | 21.4 |

where:

$D_J$ — diffusion coefficient by Jarembasz's relation (2),
$D_F$ — diffusion coefficient calculated by wave observation model (4),
$D_S$ — diffusion coefficient selected by computer simulation method (9).

On the grounds of the results, shown in table 5, one can state that the similarity of the values of diffusion coefficients $D_F$ and $D_S$ calculated for measuring data and coefficient $D_J$ calculated from geometric parameters by Jarembasz's relation has been obtained. This probably results from the fact that headings have uniform cross-sections without additional obstacles and also have relatively smooth concrete walls. It is noticeable that diffusion coefficient value depends on air flow velocity (increase in $D$ as velocity grows up). This confirms the conclusions of previous examinations of this coefficient (Gumuła et al., 1973), (Jarembasz, 1970), (Klebanow, 1974), (Lee, 1995), (Szlęzak, 1996). The higher diffusion coefficient calculated by wave observation $D_F$ and by simulation method $D_S$ than the coefficient evaluated by Jarembasz's relation may be produced by an effect on the gas admixtures propagation because a section between points $D_2$ and $D_3$, as it shown in the scheme, is the section of a working running at right angle. The Jarembasz's relation disregards such obstacles on the air path so the value of coefficient calculated from this relation is lower.

### 5.3. Evaluation of diffusion coefficient for carbon monoxide signals

The data from observations on carbon monoxide concentration were recorded in mine after shooting. The remarkable delay between the signals (over 20 minutes), causes that the value of diffusion coefficient was determined only for the first point of observation ($C_1$) approximating CO concentration signal by Klebanow's function. The results are shown in table 6.

TABLE 6

Diffusion coefficient for carbon monoxide signals

| No of observation | $t_1$ | $t_2$ | $T_{max}$ | $D_J$ | $D_K$ |
|---|---|---|---|---|---|
| 11 | 3.5 | 15.1 | 7.9 | | 61.2 |
| 41 | 2.2 | 12.5 | 6.0 | 6.87 | 62.6 |
| 61 | 2.4 | 12.8 | 6.2 | | 62.8 |

where:

$D_J$ — diffusion coefficient calculated by Jarembasz's relation (2),
$D_K$ — diffusion coefficient calculated by Klebanow's function.

Basing on the results shown in table 6, one can as certain a wide difference between the values of diffusion coefficient calculated by these two methods. On the other hand, big repeatability of coefficient $D_K$, calculated from Klebanow's function, is noticeable.

## 6. Summary

Gas disturbances occur in workings due to the activation of the admixtures source. They spread along the ventilation paths and decay step by step moving away from the source. Time and range of disturbances propagation depend on the source characteristic and ventilation conditions. The effects of methane concentration changes in the longwall area are observed within the range of many kilometres, and time of their occurrence defined by transport delay comes up even to one hour. The velocity of disturbances propagation is related to mean velocity of floating admixture (Roszczyński et al., 1992) which can be determined in an experimental way by e.g. the method of correlation function (Wasilewski, 1998). Impulse decay as moving along a working is related to diffusion effect.

Used up to the present the evaluation methods of diffusion coefficient refered to gas admixtures propagation in a form of impulse (Klebanow, 1974) or a known gas portion (Lee, 1995) either were related only to the working parameters and air flow velocity (Jarembasz, 1970). The authors of these methods did not state requirements of experimental evaluation of a diffusion coefficient under mine conditions. They did not fix the distances of measuring points, for which these methods would be still applicable. Under mine conditions at long roads of disturbances propagation, the observed signals are not only the results of diffusion effect but also of floating (considerable transport delays Fig. 11). It makes difficult and sometimes even impossible to use some methods e.g. given in paper (Gumuła, et al., 1973), or requires their modification. Besides the natural markers in a form of disturbances connected usually with technological functions and not impulses or gas portions as markers were used for evaluation of diffusion coefficient.

The values of diffusion coefficient evaluated on the basis of signals are higher than calculated from the working geometrical parameters and air flow velocity e.g. Jarembasz's method (Jarembasz, 1970). Thesr are many factors (obstructions section inequalities deflections) which can considerably increase admixture diffusion in flowing air in the workings of a real mine. This is evident for the workings of longwall type, whereas for headings at the Central Mining Rescue Station the differences of the values of diffusion coefficient for smoke signals are small.

Basing on the evaluation of diffusion coefficient for recorded signals, it has been found as follows:

- length of gas disturbance impulse (after shooting) is proportional to the root of distance from disturbance source,
- diffusion coefficient rises as air flow velocity increases,
- diffusion coefficient depends intensively on section inequality and it can come up to considerable values in case of obstacles in working section or working deflection, so under mine conditions it has to be evaluated only in an experimental way.

The used model of gas disturbances propagation allows to select a diffusion coefficient by means of the methods of computer based simulation irrespective of disturbance character. Generated from the model, the time — space distributions of gas concentration, selected by the simulation method, are in conformity with the real ones. Selection of the value of turbulent diffusion coefficient by the computer based simulation method, time — space propagation of disturbances on the basis of approximation of the measuring values of gas concentration in a mine working, has been suggested by J. Szywacz from EMAG Centre. The author would like to express his thanks to him.

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