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THE PROBLEM OF CARBON DIOXIDE EMISSIONS FROM CLOSED COAL MINE SHAFTS – THE OVERVIEW AND THE CASE STUDY

PROBLEMATYKA I WYNIKI BADAŃ WYPŁYWU DWUTLENKU WĘGLA PRZEZ ZLIKWIDOWANE SZYBY KOPALŃ WĘGLA KAMIENNEGO

Greenhouse gas emissions are a common problem noticed in every mining area just after mine closures. However, there could be a significant local gas hazard for people with continuous (but variable) emission of these gases into the atmosphere.

In the Upper Silesia area, there are 24 shafts left for water pumping purposes and gases can flow through them hydraulically. One of them – Gliwice II shaft – was selected for inspection. Carbon dioxide emission with no methane was detected here. Changes in emission and concentration of carbon dioxide around the shaft was the aim of research carried out.

It was stated that a selected shaft can create two kinds of gas problems. The first relates to CO_2 emission into the atmosphere. Possible emission of that gas during one minute was estimated at 5,11 kg_{CO_2}/min. The second problem refers to the local hazard at the surface. The emission was detected within a radius of 8m from the emission point at the level 1m above the ground.

These kinds of matters should be subject to regular gas monitoring and reporting procedures.

Keywords: carbon dioxide emission, gas emission, gas hazard, greenhouse gas, abandoned mine, closed mine

Emisja gazów cieplarnianych jest problemem dotyczącym wszystkich zagłębi górniczych węgla kamiennego na świecie. Problem ten nie kończy się wraz z likwidacją zakładów górniczych. Jako najbardziej prawdopodobne źródła emisji metanu lub/i dwutlenku węgla ze zlikwidowanej kopalni uznawane są uskoki tektoniczne, zlikwidowane lub nieczynne szyby kopalniane, obszary wychodni pokładów węgla, krawędzie dawnej płytkiej eksploatacji itd. (Czaja, 2011; Dziurzyński et al., 2004; Sułkowski & Wrona, 2006). Wypływy gazów cieplarnianych na powierzchnię terenu po pierwsze oddziałują negatywnie na stan atmosfery, a po drugie mogą tworzyć lokalne, tym niemniej przejściowe, zagrożenie dla bezpieczeństwa powszechnego.

W pierwszym rozdziale artykułu przedstawiono obecny stan wiedzy na świecie dotyczący poruszanego zjawiska. Stanowiło to przesłankę do podjęcia badań, których rezultaty przedstawiono w kolejnych

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rozdziałach. Stwierdzono także, że w żadnym kraju nie są prowadzone procedury pomiarów i raportowania emisji gazów cieplarnianych z obiektów tego typu.

Następnie przedstawiono wyniki badań dotyczących emisji dwutlenku węgla z wybranego, nieczynnego szybu górniczego oraz imisji tego gazu w otoczeniu szybu.

Na obszarze Górnego Śląska pozostawiono 24 szyby kopalniane dla prowadzenia odwadniania. Są to szyby aerodynamicznie drożne. Do badań wybrano jeden z nich, nieczynny szyb „Gliwice II". Podczas badań wstępnych stwierdzono znaczące ilości wypływającego dwutlenku węgla przy braku obecności metanu w mieszaninie gazów.

Jako, że emisja gazów ze zlikwidowanej kopalni ku atmosferze może być porównana z emisją gazów ze zrobów do powietrza płynącego poprzez czynna kopalnię (Krach, 2004; Drzewiecki, 2004), uznane jest, że zależy od wielu czynników (w tym głównie od wahań ciśnienia atmosferycznego, ale także od różnicy gęstości gazów i powietrza atmosferycznego (Grzybek, 2012; Wrona et al., 2014).

Harmonogram badań przewidywał okresowe pomiary od lutego do maja 2014r. głównie w trakcie zniżek barycznych.

Pomiary emisji prowadzono na trzech zidentyfikowanych otworach wylotowych w płycie zamykającej szyb (Fig. 2-3). W każdym otworze przeprowadzono badania wstępne dotyczące określenia jednorodności koncentracji gazu w całym profilu. Do pomiarów prędkości powietrza zastosowano metodę trawersu ciągłego.

Stwierdzono, że największa wartość emisji dwutlenku węgla wyniosła 2,69 m^3/min (Tab. 2), co przy uwzględnieniu średniej gęstości tego gazu (1,9 kg/m^3) odpowiada 5,11 kg/min. Otrzymany wynik jest wartością chwilową, natomiast daje pogląd na możliwą skalę maksymalnej emisji. Otrzymano także nowe wyniki dotyczące wpływu różnicy pomiędzy temperaturą gazu, a temperaturą atmosfery na wielkość emisji gazu. Dnia 14.03.2014 pomimo zniżki barycznej o tendencji –0,53 hPa/h wielkość emisji dwutlenku węgla dochodziła do 1,66 m^3/min (Tab. 2). Natomiast 28.02.2014 pomimo spadku ciśnienia o mniejszej wartości tendencji barycznej, wynoszącej –0,4 hPa/h, wartość emisji była największa. Analizując wyniki przeprowadzonych pomiarów psychrometrycznych powietrza atmosferycznego i gazu stwierdzono, że w pierwszym przypadku różnica temperatur gazu i atmosfery wynosiła –0,1°C, natomiast w drugim przypadku 6,0°C.

Pomiary imisji dwutlenku węgla wokół szybu „Gliwice II" prowadzono na poziomie gruntu i na wysokości 1m nad gruntem w oparciu o założoną siatkę pomiarową (Fig. 3). W każdym z punktów pomiarowych pozostawiono detektor gazów MulitRae Plus (z automatycznym zapisem danych) na czas dwóch minut z ustawionym interwałem próbkowania 30 sekund. Otrzymane cztery wyniki dla każdego punktu następnie uśredniono. Mapy izolinii stężenia dwutlenku węgla wokół szybu Gliwice II wykonano w programie Surfer 8. Przykład z 21.05.2014 przedstawiono na Fig. 5. Stwierdzono, że zasięg podwyższonego stężenia dwutlenku węgla może sięgać 8 m od punktowego źródła emisji na wysokości 1 m, a na poziomie gruntu może tę wartość przekraczać.

Słowa kluczowe: emisja dwutlenku węgla, emisja gazu, zagrożenie gazowe, efekt cieplarniany, zlikwidowana kopalnia, nieczynna kopalnia

1. Introduction

The emission of greenhouse gases from abandoned mines is a common problem observed in every coal basin (Sułkowski & Wrona, 2006).

In Poland, it was stated that closed shafts are the second most probable path of gas migration to the surface (Czaja, 2011) even though they are the most easily accessible places for possible emission detection. This thesis is the basis for the analysis and the results which are presented in this article.

Experiences from other coal basins are summarized below.

a) United States

This problem was the point of research undertaken by the Environmental Protection Agency in 2004 (U.S Report, 2004).Their main conclusions are that annual methane emission from abandoned or closed mines can be estimated at 8-10% of the global value. Another significant point was that no country in the world leads official gas emission reporting of this type. It must be added that the work only referred to CH_4 (without including CO_2 emission). The estimated amount of CH_4 emission from abandoned mines in the U.S in 2000 was 385 mln m^3.

b) United Kingdom

This problem has been reported in United Kingdom for almost 30 years (Hall et al., 2006; Creedy, 1989). Almost 900 coal mines have been closed down and a gas hazard has been reported in 75 of them (Creedy, 1998). A gas hazard was connected with a person's death in the area of Northumberland and it resulted in the implementation of compulsory law regulations for gas measurement and classification.

c) France

In France, methane emission was detected coming from shallow goafs (Pokryszka et al., 2005) It was noticed that in the area of a children's playground, there was intensive methane emission (up to 85 $cm^3/min/m^2$).

d) Germany

In Germany the problem has been reported since 1976 (Eicker, 1987; Otto, 2010). Longterm research has indicated that when pressure falls, there is an increase in methane and carbon dioxide emission above abandoned shafts. Maximum concentration of CO_2 measured in 1978 was up to $30\%_{vol}$, and the total volume flow was up to 1000 m^3/h. At the same time, oxygen concentration decreased to $5\%_{vol}$. When considering methane drainage systems from closed mines, one can observe that methane emission has been decreasing in subsequent years. For example in 1980 the emission rate was 270 m^3 CH_4/h, and in 1983 was 50 m^3 CH_4/h.

e) China

Research into greenhouse gas emissions conducted by prof. Creedy (Creedy et al., 2003) stated that 50 coal mines out of a total number of 120 closed mines are a potential danger to the atmosphere. The average greenhouse gas emissions were computed at the level of 200 dm^3/s and their annual emission was estimated as $4{,}4 * 10^6$ Mg CO_2, although one of the selected mines emitted about 420 mln m^3 CH_4 per year. Partial usage of methane drainage for energy purposes or partial flooding are recommended for emission prevention (Krause & Pokryszka, 2013). This statement contradicts conclusions drawn by J. Hall (Hall et al., 2006). He maintained the thesis that greenhouse gas emissions can be noticed even above flooded mines.

f) Czech Republic

The Upper Silesia coal basin is divided into the Polish and Czech parts. Czech closed many mines in the 90's and the problem of gas emission at the surface was detected at that time (Prokop, 2001; Novotny et al., 2001). As a result of methane migration to the surface in 1999, there was a methane explosion in one of the houses in the city of Ostrava and one person died. There were also many similar examples of methane or carbon dioxide presence in cellars, garages etc.

g) Ukraine

The most important cases of gas emission were noticed in the Stachanowskij area (Kasimov et al., 1999). According to research undertaken by Ukrainian authors, there were 73 cases of methane ignition and 3 cases of blackdamp in the houses. The total number of people injured by the presence of gas was 91.

h) Australia

In this region, research was carried out by L. Lunarzewski (Lunarzewski, 2009). The main research findings were:

- Coal mine goafs in Australia have been classified in relation to the mining, hydrogeological and ownership conditions;
- The amount of methane from coal mine goafs was estimated using emission decay curves and related mathematical formulae thus avoiding difficulties in identifying all gas sources and their magnitude;
- The proposed coal mine goafs have been classified in relation to the case studies carried out on selected underground coal mines which defined eight various categories in relation to similar mining, gassy and geological conditions;
- Where some typical data is lacking, site investigation may be required involving drilling, gas monitoring, water and gas pumping tests.

i) Poland

In the 90's in Poland, there were significant and dangerous examples of methane and carbon dioxide emissions from abandoned mines within The Upper and Lower Silesia coal basins (Kotarba, 2002; Szlazak et al., 2003). All coal mines in The Lower Silesia area were closed at once. The coal mines in The Upper part have been partly closed and that process is expected to continue in the future. The range of the restructuring process in Polish coal mining 1991-2008 is shown in Fig. 1. The number of active coal mines was reduced from 70 to 31, the amount of coal output was decreased from 140 to 83,4 mln Mg, and employment fell from 353 000 to 119000 people (Fig. 1).

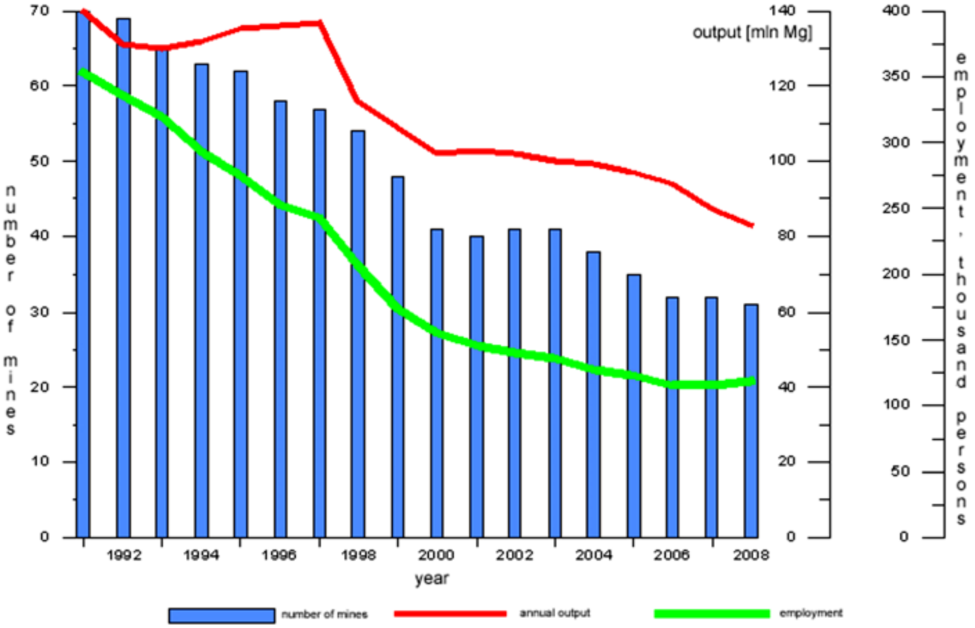

Fig. 1. The range of restructuring process in Polish coal mining 1991-2008 (WUG Report, 2009)

In each case, a gas hazard was detected immediately after termination of mine ventilation. The results of research conducted in The Lower Silesia showed that main sources of methane and carbon dioxide migration were faults (46% of total number of cases), edge lines of shallow exploitation and shafts (about 30%), porphyry (about 15-20%) and outcrops (the rest). The maximum concentration of methane was $25{,}7\%_{\text{vol}}$ and the maximum concentration of carbon dioxide was $10{,}5\%_{\text{vol}}$ (Krzystolik & Kobiela, 2002; Czaja, 2011).

Abandoned shafts, drifts, gaps and faults could be considered as possible sources of gas emissions. The kinds of gas flow are listed below (Grzybek, 2012; Kulczycki & Grzybek, 1999; Wrona et al., 2014):

- Diffusive – caused by a gas concentration gradient which occurs between different elements of the coal matrix.
- Filter – through a porous medium – caused by gas pressure balancing in the gaps. Flow to the surface is the effect of pressure difference.
- Convective – caused by the buoyancy phenomenon, including different densities of gases in underground conditions.
- Hydraulic – taking place in empty excavations, drilling holes and gaps which have connections with the surface which are under the influence of external forces (atmospheric pressure changes and increase of underground water level).

According to Table 1 in the Upper Silesia region, there are 24 shafts which are left for water pumping. They should be considered as sources of greenhouse gases emission with possible hydraulic flow.

TABLE 1

The number of closed shafts and their total depth in Polish coal mines after 1990 (Czaja, 2011; WUG Report, 2009)

No.	**Group of mines**	**Closed shafts**	
		The number	**Summary depth[m]**
1.	The coal mines belong to the coal company – Kompania Węglowa S.A. (Upper Silesia)	75	34 339,5
2.	Other coal mines (Upper Silesia)	32	16 135,5
3.	Former independent mines (Upper Silesia)	134	55 947,0
4.	The coal mines in Lower Silesia	67	35 550,0
5.	**Shafts which are left for underground water pumping**	**24**	**13102,0**
	Total:	332	155074,0

According to the state of the art (Wrona, 2010), the process of gas flow through a shaft depends on:

a) the gas bearing capacity of a seam (in the case of CH4 emission) (Grzybek, 2012),
b) the goafs – oxygen contact area,
c) the geological structure, including height of overburden,
d) the underground water level increase and CO2 saturation in water,
g) the atmospheric pressure changes (Wrona, 2005).

2. The Measurements

The measurements were based on Polish Standard PN-EN 15259 „Jakość powietrza. Pomiary ze źródeł stacjonarnych, Wymagania dotyczące odcinków pomiarowych, miejsc pomiaru, celu i planu pomiaru oraz sprawozdania z pomiaru" (Air quality. Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report) (PN-EN 15259). The plan of the measurements was based on the above mentioned standard, on Namieśniak's Measuring Guide Book (Namieśniak et al., 1995) and on (Górka et al., 2000) The maps of carbon dioxide concentration around the shaft were developed using Surfer Software and PN-Z-04008-02:1984 „Ochrona czystości powietrza. Pobieranie próbek. Wytyczne ogólne pobierania próbek powietrza atmosferycznego (imisja)" (PN-Z-04008-02:1984) and (Juda & Chróściel, 1974).

2.1. The Measurement Location

The closed shaft Gliwice II was selected as a working area for future investigation (Fig. 2). It is situated in the city of Gliwice, Bojkowska street 37. The shaft is left for water pumping purposes and belongs to Centralny Zakład Odwadniania Kopalń w Czeladzi (Central Plant of Water Pumping in Czeladź).

The area is presented in Fig. 2.

Fig. 2. The area of Gliwice II shaft. 1 – the building of Higher School of Economy in Gliwice, 2 – two symmetrical points of emission, 3 – pipelines for water pumps, 4 – the outlet of the fan no. 1, 5 – the outlet of the fan no. 2

2.2. The Methodology

The process is considered as constant with different and variable factors (air pressure and temperature) influencing it.

Four points were carried out for "in situ" emission measurements (Namieśniak et al., 1995) during preliminary surveys (points no 2 (having 2 outlets), 4 and 5). The overview is presented in Fig. 2 and 3).

Point 2 (Fig. 3) consists of two symmetrical outlets with dimensions 0,23 m × 0,68 m. The cross-section area of each outlet is 0,1564 m^2.

a) Point 4 is the outlet of the fan no.1 which allows for underground inspections. The cross-sectional area equals 0,125 m^2.
b) Point 5 is the outlet of the fan no.1 which is also dedicated to ventilation purposes in the lower parts of the shaft. The cross- sectional area equals 0,125 m^2.

It was stated that there is significant concentration of carbon dioxide and the gas concentration is constant in the profile. As a result – continuous traverse method to establish average velocity was selected (Wacławik, 2010).

Measurements were planned each month, including collection of meteorological data.

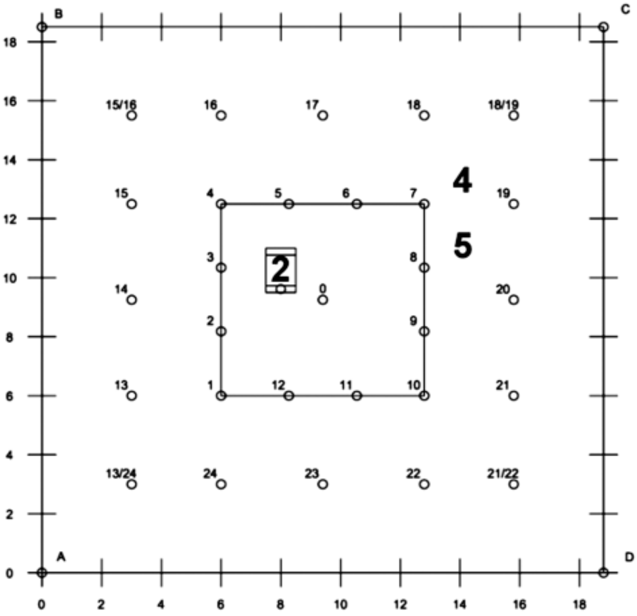

Fig. 3. Measuring mesh including location of measuring points no. 2, 4 and 5

2.3. The Instruments

The following devices have been put into operation: a portable detector MultiRAE Plus, an Assmann's psychrometer, a digital anemometer μAS (Fig. 4]), a gas detector WG-2M.

General meteorological data has been collected from Central Mining Institute's meteorological station [internet source 1]. Pressure changes above the shaft have been measured with a portable barometer – Barolux.

Fig. 4. Air velocity measurements at point no. 2

3. The Results and The Discussion

The results are divided into two sections: the first refers to carbon dioxide emission assessment and the second gives information about gas concentration above the shaft.

3.1. The emission

Selected results from 02.2014 to 05.2014 are given in Table 2.

The maximal value of CO_2 emission was observed on 28.02.2014 at 10:36. It was 2,69 m^3/min. The pressure fall lasted for 20 hours with average baric tendency –0,4 hPa/1h. The difference in temperature between gas and atmosphere was 5,4°C.

On 14.03.2014 average baric tendency was higher than on 28.02.2014. It was –0,53 hPa/h, however, the emission rate was lower. It was 1,66 m^3/min at 16:42. The reasons for this is that there was no difference in gas and atmospheric temperature ($\Delta t_d = 0{,}1$°C) and a shorter pressure fall time (8 h 12’).

On 21.05.2014, the average baric tendency was –0,2 hPa and the pressure fall lasted for 5 h. The dry bulb temperature difference was –8,9°C. The emission was 0,36 m^3/min at 15:00.

The last test result example obtained during the pressure fall is from 23.05.2014. The baric tendency was low –0,16 hPa/h, it lasted for 12 h and the dry bulb temperature difference

TABLE 2

The results of CO2 measurements from the points no. 2, 4 and 5

Date	Hour	V_{CO_2} point 2 [m^3/min]	V_{CO_2} point 4 [m^3/min]	V_{CO_2} point 5 [m^3/min]	Total CO_2 emission [m^3/min]	Pressure at the beginning of fall or increase [hPa]	Pressure during the measurement [hPa]	*bt* [hPa/1h]	Time from the beginning of fall or increase	Δt_d gas-atmosphere [°C]	Δt_d the result [°C]
28.02.2014	9:15	1,13	0,28	0,57	**1,98**	980,0	972,0	–0,4	20h	11,2- 5,2	6,0
	10:36	1,42	0,34	0,93	**2,69**					12,4 – 7,0	5,4
14.03.2014	10:20	0,34	0,14	0,32	**0,80**	987,0	982,6	–0,53	8h12’	12,0-12,1	–0,1
	15:22	0,58	0,45	0,58	**1,61**						
	16:42	0,73	0,39	0,54	**1,66**					13,8-16,8	–3,0
21.05.2014	10:00	0,11	0,05	0,05	**0,21**	982,7	981,7	–0,2	5h	14,8-23,1	–8,3
	15:00	0,24	0,07	0,05	**0,36**					15,3-24,2	–8,9
23.05.2014	9:00	0,08	— (out of range)	— (out of range)	**0,08**	977,6	975,7	–0,16	12h	14,2-24,3	–10,1
	12:00	0,15	— (out of range)	— (out of range)	**0,15**					14,9-27,1	–12,2
30.05.2014	8:30	0,0	0,0	0,0	**0,0**	-	978,5	+	—	—	—

bt — average baric tendency, average change of pressure during 1h, hPa/1h,
Δt_d — dry bulb temperature difference, °C.

TABLE 3

The results of CO2 measurements from the points no. 2, 4 and 5 including air velocities and CO_2 concentration

Date	**Hour**	V_{CO_2} **point 2 [m³/min]**	***w*** **point 2 [m/s]**	CO_2 **concentration point 2 [%vol.]**	V_{CO_2} **point 4 [m³/min]**	***w*** **point 4 [m/s]**	CO_2 **concentration point 4 [%vol.]**	V_{CO_2} **point 5 [m³/min]**	***w*** **point 5 [m/s]**	CO_2 **concentration point 5 [%vol.]**	**Total** CO_2 **emission [m³/min]**
28.02.2014	9:15	1,13	2,42	5,00	0,28	1,10	3,50	0,57	1,60	4,80	**1,98**
	10:36	1,42	2,45	6,20	0,34	1,20	3,80	0,93	2,13	5,80	**2,69**
14.03.2014	10:20	0,34	1,30	2,80	0,14	1,13	1,70	0,32	1,60	2,70	0,80
	15:22	0,58	1,7	3,65	0,45	1,65	3,65	0,58	1,95	3,90	**1,61**
	16:42	0,73	2,27	3,45	0,39	1,66	3,20	0,54	1,92	3,70	**1,66**
21.05.2014	10:00	0,11	1,15	1,10	0,05	0,90	0,80	0,05	0,85	0,80	**0,21**
	15:00	0,24	1,39	1,90	0,07	1,10	0,90	0,05	0,70	1,00	**0,36**
23.05.2014	9:00	0,08	1,06	0,90	— (*lack of data)	—	0,30	— (*lack of data)	—	0,35	**0,08**
	12:00	0,15	1,20	1,50	— (*lack of data)	—	0,90	— (*lack of data)	—	0,91	**0,15**
30.05.2014	8:30	0,0	-	0,06	0,0		0,06	0,0		0,06	**0,0**

* unauthenticated data obtained with application of a vane anemometer, rejected for further analysis

was –12,2°C. The total emission of CO_2 was 0,15 m^3/min at 12:00. However, it was not possible to detect CO_2 emissions. Obtained data was unauthenticated and it was rejected for further considerations.

On 30.05.2014 there was a pressure increase. No gas emission from the shaft was detected. It was observed that there was no gas flow into the air nor flow in the opposite direction.

The results obtained contradict the German statement (Eicker, 1987) that gas emission from a shaft has a linear relation only to the pressure value and they match the results obtained during previous research undertaken within The Upper Silesia Coal Basin, e.g. (Sułkowski & Wrona, 2006).

When considering CO_2 it should be observed that the emission is a function (equation 1) of the following factors:

- the average baric tendency, (*bt*),
- the time of pressure fall, (*t*),
- the difference of gas – ambient densities, (ρ) (which at first is represented by the dry bulb temperature difference and is followed by the individual gas constant etc.

$$V = f(bt, t, \rho) \tag{1}$$

The significance of several factors should be further investigated.

Using the results obtained, it is possible to make general estimations of possible carbon dioxide emissions from the shaft “Gliwice II’ that could be observed during one day with meteorological conditions as described on 28.02.2014.

According to Table 2 measured maximal rate of carbon dioxide emission is 2,69 m^3/min. This result can be different from real values, although it gives general knowledge about the range of the emission and amount of emitted green house gas to the atmosphere. Knowing average density of carbon dioxide (1,9 kg/m^3) it gives rate of emission equals 5,11 kg_{CO_2}/min.

This value should be documented and reported within frames of air protection programs with application of gas manual and automatic monitoring systems, e.g. (Wasilewski, 2008).

3.2. Carbon dioxide concentration map

The following research has never been done before in Poland and the author doesn’t know of any similar results following abandoned (closed) coal mine shafts.. According to the latest (in situ) experiments, the main aim of the measurements was to obtain preliminary results and develop a possible methodology for future analysis.

The measurements were taken at ground level (0 m) and 1m level moving from point no. 1 to point no. D. A gas detector was left at each point for two minutes, the data login in the detector was set for 30 second intervals which gave a total of 4 results for the point. Then the value was averaged.

The maps were produced on Surfer Software. The example of carbon dioxide concentration around selected shafts from 21.05.2014 is presented in Figure 5. The wind was from East direction, however during the measurements (9:00-12:00) the wind speed did not exceed 0,8 m/s.

On the left side of figure 5, there is a CO_2 concentration map which represents gas isolines at 0m level. Higher values of CO_2 concentration are clearly visible in the area around point no. 2 (according to Fig. 3). Points 4 and 5 are represented by gas isolines 1,2$\%_{vol}$ and 1,0$\%_{vol}$ in the

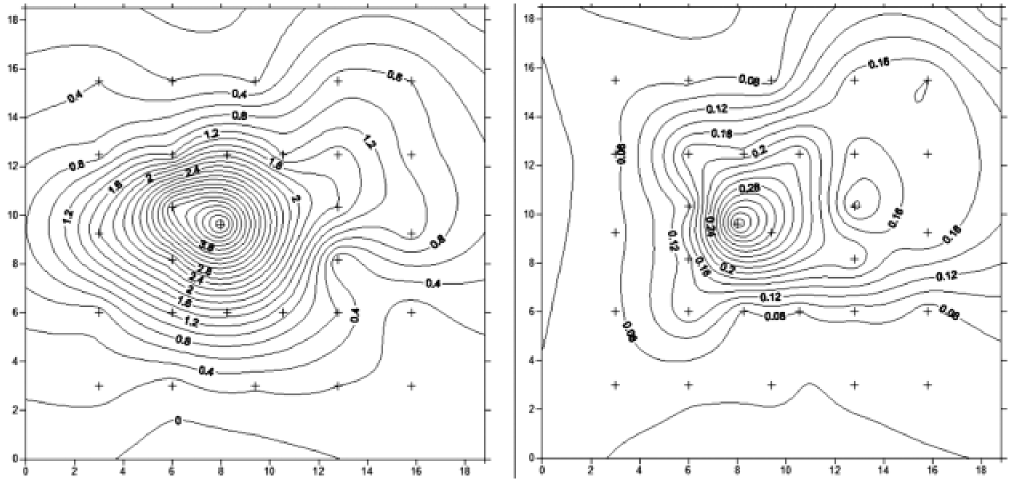

Fig. 5. The example of CO_2 concentration in the selected area. On the left – at the surface (level of the ground 0 m), on the right – at 1m. Measurements were taken on 21.05.2014. The results are presented in %vol unit. Axis units are meters

right-upper part of the figure. On the right side of Figure 5 the distribution of the gas isolines at the level of 1m is different. Although three points of emission can easily be detected by the gas isolines above point 2 and gas isolines in the right-upper part $0{,}16\%_{\mathrm{vol}}$. It can be observed that CO_2 at the 1 m level is diluted but still noticeable. On 21.05.2014 the background level of CO_2 was 600 ppm ($0{,}06\%_{\mathrm{vol}}$) which leads to the conclusion that the area of higher gas concentration is detected even up to 8 m from the source of emission.

4. Conclusions

1. Each abandoned or closed coal mine shaft should be considered as a possible source of greenhouse gas emissions. The results presented in the article prove that carbon dioxide emission could be significant. Literature overview indicates that in other cases methane should be expected, too.
2. The maximal detected CO_2 emission was $2{,}69\ m^3$/min. Including carbon dioxide density it equals $5{,}11\ kg_{CO_2}$/min. According to USA research since 2004 (Report, 2004), no country in the world leads official gas emission reporting of this type. The results presented above show that the current situation should change and these subjects should be covered by regular monitoring and reporting in national air protection programmes.
3. Carbon dioxide emission can create local gas hazards above an abandoned or closed shaft. Maps of CO_2 isolines at levels of 0 m and 1m show that the gas could be detected up to 8 m from the source of emission. It leads to the conclusion that each site of that type should have restricted access.

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References

Creedy D.P., 1989. *Geological sources of methane in relation to surface and underground hazards*. Methane facing the problems symposium, Nottingham, 26-28 September 1989.

Creedy D.P., 1998. *Gas in abandoned mines: a hazard and a resource?* Proceedings of International Conference on Coal-Bed Methane – Technologies of Recovery and Utilisation. Wyd. GIG, Ustroń, s. 507-524.

Creedy D.P., Armstrong W., Sage P., Hu Yuhong, Sun Xin, Jin Ling, Zhang Wenbo, 2003. *Reducing the Environmental Impact of Abandoned Coal Mines in China*. 3rd International Methane and Nitrous Oxide Conference, 17-21. XI.2003, Beijing, China.

Czaja P., 2011. *Polskie doświadczenia w likwidacji szybów – likwidacja zakładu górniczego i likwidacja szybów – wymogi formalno – prawne*. Wiadomości Górnicze, 3/2011, s. 167-174.

Drzewiecki J., 2004. *Methane emission from longwalls and its relationship to advance rate*. Archives of Mining Sciences, Vol. 49, Iss. 2.

Dziurzyński W., Krach A., Krawczyk J., Pałka T., 2004. *Migracja gazów z szybu zlikwidowanej kopalni*. Mat. 3 Szkoły Aerologii Górniczej, Zakopane 12-15.10.04, s. 167-180.

Eicker H., 1987. *Verlauf und Beherrschung der Ausgasung abgeworfener Grubengebaude*. Gluckauf-Forschungshefte, 48 nr 6/1987, s. 324-328.

Górka P., Kowalski S., Kozielska B., Melaniuk-Wolny E., Oparczyk G., Zajusz-Zubek E., Żak M., 2000. *Badania zanieczyszczeń powietrza. Cz. I. Gazowe substancje zanieczyszczające*. Wydawnictwo Politechniki Śląskiej, Gliwice.

GrzybeK I., 2012. *Studium uwarunkowań emisji gazów ze zlikwidowanych kopalń SW części GZW*. Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie, nr 1-5, 8-10/2012, Katowice.

Hall J., Younger P., Glendining S., 2006. *Is minewater a source of hazardous gas?* IAEG2006 Paper number 349, The Geological Society of London, p. 1-6.

Juda J., Chróściel S., 1974. *Ochrona powietrza atmosferycznego*. Wydawnictwa Naukowo-Techniczne, Warszawa.

Kasimov O.I., Kochera V.N., Yakovenko E.A., Yermakov V.N., 1999. *Prediction and prevention of gas danger emissions from closed mines to the surface*. Proc. 28 Int. Conf. Safety Mines res. inst., vol. II, June 1999, Sinaia, Romania.

Kotarba J., 2002. *Gas hazard in The Near-Surface Zone of the Wałbrzych Coal Mine Closure: Geological and Geochemical Controls*. Wyd. „Akapit", Kraków, 2002.

Krach A., 2004. *Influence of Barometric – Pressure Variation on Methanbe Concentration in Air Flow From Longwall Region with Adjacent Goaf – A Mathematical Model and Calculation Algorithm*. Archives of Mining Sciences, Vol. 49, No 1, p. 43-53.

Krause E., Pokryszka Z., 2013. *Badania emisji metanu ze zlikwidowanych zatopionych kopalń*

węgla kamiennego. Journal of Sustainable Mining, 12/2013, no. 2, p. 39-43.

Krzystolik P., Kobiela Z., 2002. *Mechanizm migracji gazu na powierzchnię likwidowanych kopalń Zagłębia Wałbrzyskiego*. Przegląd Górniczy, 2/2002, s. 8-14.

Kulczycki Z., Grzybek I., 1999. *Gazy kopalniane jako zagrożenie dla bezpieczeństwa powszechnego*. Miesięcznik WUG, nr 1/1999, s. 16-25.

Lunarzewski L., 2009. *Gas emission expert model for abandoned coal mine" Lungas Pty Limited*. ACARP 2008, project No. C17058, Final Report, July 2009.

Mining State Authority Report, 2009. *Raport OSG/8/2009 w sprawie zlikwidowanych szybów w zakładach górniczych węgla kamiennego GZW po 1990 r*., Katowice 2009.

Namieśniak J. Łukasiak J. Jamrógiewicz Z., 1995. *Pobieranie próbek środowiskowych do analizy*. Wydawnictwo Naukowe PWN, Warszawa.

Novotny R., Platenik M., Takla G., Kral V., 2001. *Reduction of Uncontrollable Mine Gas Emission in The Czech Part of Upper Silesian Hard Coal Basin Devastated By Past Mining Activity*. Proc. of The 7th International Mine Ventilation Congress, 17-22.06.2001, Kraków, s. 127-131.

Otto F., 2010. *Protection of Houses against methane*. 11/2010 Geotechnics 2010 – Gliwice, Poland: ERASMUS – lectures materials.

PN – EN PN-EN 15259 *Jakość powietrza. Pomiary ze źródeł stacjonarnych. Wymagania dotyczące odcinków pomiarowych, miejsc pomiaru, celu i planu pomiaru oraz sprawozdania z pomiaru* (BS EN 15259:2007 Requirements for measurement sections and sites and for the measurement objective, plan and report), Warszawa, 2011.

PN-Z-04008-02:1984 *Ochrona czystości powietrza. Pobieranie próbek. Wytyczne ogólne pobierania próbek powietrza atmosferycznego (imisja)*. Warszawa.

Pokryszka Z., Tauziède C., Lagny C., Guise Y., Gobillot R., Planchenault J.M., Lagarde R., 2005. *Gas Migration From Closed Coal Mines to The Surface Risk assessment methodology and prevention means*. Post-Mining 2005, November 16-17, Nancy, France.

Prokop P., 2001. *Gas Leak Effects on Environment of Ostrava Basin*. Proc. of 7th Intern. Mine Vent. Congress 17-22.06.2001, Kraków, s.137-139.

Report U.S. Environmental Protection Agency, 2004. *Methane emissions from abandoned coal mines in the united states: emission inventory methodology and 1990-2002 emissions estimates*. April, 2004.

SułkowskI J., Wrona P., 2006. *Mathematical Model Of Gas Out Flow From Abandoned Coal Mine Through Untight Shaft Under The Influence Of Atmospheric Pressure Changes*. Archives of Mining Sciences, Vol. 51, Iss. 1, p. 97-107.

Szlązak N., Obracaj D., Borowski M., 2003. *Ocena stanu zagrożenia emisją gazów kopalnianych terenów pogórniczych*. Mat. Seminarium „Metan i inne zagrożenia współwystępujące – teoria i praktyka" NOT-SITG ROP 2003, 29.10.2003 Rybnik, s. 191-207.

Wacławik J., 2010. *Wentylacja kopalń*. t. 1,2, Wydawnictwa AGH, Kraków.

Wasilewski S., 2008. *Modern systems of gas hazard monitoring in Polish hard coal mines*, Archives of Mining Sciences, Vol. 53, iss. 4, p.511-524.

Wrona P., 2005. *Possibilities of mine gases outflow prediction during pressure drops considering abandoned shaft located in old coal mining area*. Glückauf-Forschungshefte, 66, nr 3, p. 103-106.

Wrona P., 2010. *Przepływ powietrza zrobowego w zlikwidowanych szybach w stanach awaryjnych w świetle badań modelowych*. Przegląd Górniczy, 12/2010, s.148-151.

Wrona P., 2014. *The Problems of Gas Emission From Closed Down Mines in The Area of The Upper Silesia*, Inżynieria Górnicza, 2/2014, p. 27-30.

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