ANALYSIS OF THE SCALE OF METHANE HAZARD IN POLISH HARD COAL MINES

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Abstract: In the majority of Polish mines, the exploitation of hard coal is accompanied by the release of considerable amounts of methane. Being flammable and explosive, methane may form an explosive mixture with air once it appears in mine workings. For this reason, the methane hazard is recognised as one of the ventilation risks in the mining industry. This process leads to the formation of air and methane mixture, whose considerable amounts permeate into the atmosphere and the natural environment. This phenomenon is extremely unfavourable because methane is, besides carbon dioxide, yet another gas that exacerbates the greenhouse effect. For this reason, it is increasingly more common to equip mines with methane collection systems in the process of demethylation. These play a vital role for both the natural environment and the safety of work in mines. A reduction of the methane content in headings increases the safety of the working crew and enhances the effectiveness of mining production. The article presents an analysis of the methane-related hazard based on methane emissions during mining exploitation. The analysis was based on the data concerning the amount of methane emitted into the atmosphere and collected by methane extraction systems from 16 coal mines. It led to identification of homogenous mines with similar values of the absolute methane-bearing capacity and ventilation methane-bearing capacity as well as with similar amounts of methane collected by methane extraction systems. The analysis was performed using the non-hierarchical k-average method, which belongs to the group of algorithms for analysing clusters. As a result, the mines were divided into the assumed number of groups. The results obtained made it possible to determine a group of mines in which, in the Author's opinion, similar systems can be applied for controlling and reducing the methane hazard. These results also open up numerous possibilities for undertaking joint business ventures by the mines in terms of using the collected methane and implementing preventive measures.

Keywords: coal mine, methane emission, cluster analysis, hazard, environmental

1. INTRODUCTION

In the majority of Polish mines, the exploitation of hard coal is accompanied by the release of considerable amounts of methane (Brodny and Tutak, 2016a, Brodny and Tutak, 2016b; Brodny and Tutak, 2016c; Brodny and Tutak, 2018, Sue et al., 2011; Wrona, 2017). Being flammable and explosive, methane may form an explosive mixture with air once it appears in mine workings. For this reason, the methane hazard is recognised as one of the ventilation risks in the mining industry (Korban, 2015). The risk arising out of the methane hazard is related to the consequences which may occur in the event of methane ignition and explosion. To avoid such dangerous situations, mine headings must be thoroughly ventilated. When mixed with air, methane is transported to the surface and emitted into the atmosphere of the environmental system. Currently, it is increasingly common for methane to be collected by methane extraction systems installed in underground headings. Thus collected, it is supplied to a methane drainage station, where it is mostly used for economic purposes.

The emission of methane into the atmosphere along with the air transported from the underground part of a mine or from methane extraction systems is a very unfavourable phenomenon (Brodny and Tutak, 2016d; Isaksen, 2014; Wrona, 2017). This is because the gas is the second (after carbon dioxide) most powerful contributor to the global greenhouse effect. Admittedly, carbon dioxide has the largest share in the formation of the greenhouse effect, but methane as a gas contributes much more to this effect. Its greenhouse effect index is 21 times higher than that of CO_2. As a result, 1 tonne of emitted methane causes the same greenhouse effect as 21 tonnes of carbon dioxide. It is estimated that the methane emission level from coal mines worldwide represents approximately 8% of the total emission of this gas into the atmosphere (Sue et al., 2011). The methane hazard should therefore be considered in two aspects: firstly, as a hazard affecting the safety of hard coal production and, secondly, as a hazard contributing to the deterioration of the greenhouse effect (Brodny and Tutak, 2016a; Korban, 2015). In both cases, the hazard was measured by the amount of methane released into the atmosphere during coal exploitation. Each year in the world, as a result of coal exploitation, approximately 28 billion cubic metres of CH_4 are emitted into the atmosphere. The problem of methane is also present in Polish mines. In 2016 it was equal to above 933.76 million m^3 of CH_4, whereas in underground methane drainage system covered about 342.1 million m^3 of CH_4 and air ventilation into the atmosphere carried away about 591.66 million m^3 of this gas (Patyńska, 2017). The emission of methane into the atmosphere from methane extraction systems is caused by the impossibility to utilize this gas for economic purposes. This situation is frequently caused by improper parameters of this gas.

The majority of coal seams exploited in Polish mines have high methane content. As a result, the methane hazard is very common. The magnitude of this hazard is determined by the amount of methane emitted into the mine's atmosphere during mining works as well as by the amount of methane collected by methane extraction systems. The level of methane hazard in mines varies significantly. As a consequence, mines can be divided according to similar methane-related conditions. Therefore, the present article presents such a division of mines. The primary objective of the paper is to determine the balance of methane quantities produced in Polish hard coal mines, with account being taken of its quantity emitted into the natural environment and collected by methane extraction systems. These values were considered with regard to the particular mines. Using the non-hierarchical grouping method made it possible to divide the mines into similar groups according to the division criteria adopted. This served as the basis for dividing the mines into groups of similar parameters. The results obtained can be used for taking more decisive actions to improve the methane-related safety. They also indicate potential partners for developing and undertaking common or similar preventive measures. These measures may involve, for example, joint collection and management of methane. It is also appropriate that the mines from the particular groups, created on the basis of the conditions adopted, develop a joint programme for combating this hazard.

The results also show the great problem posed by methane in terms of the natural environment and the work safety in mines. It is therefore necessary to take various types of actions aimed at reducing its negative environmental footprint and improving the safety of mining operations.

2. METHODOLOGY OF RESEARCH

The analysis encompassed a comparison of methane quantities produced in Polish coal mines in terms of its quantity emitted into the natural environment and collected by methane extraction systems. It was carried out on the basis of the data from the Annual Report on the State of Basic Natural and Technical Hazards in the Hard Coal Mining Industry in 2016. The classification analysis encompassed 16 mines, two of which are composed of 4 sections. In the analysis, each section of these mines was treated as a separate entity. Each entity was characterised by four indicators. The input data for the particular entities have been summarised in Table 1. Then, they underwent statistical processing and the resultant coefficient of variation has been presented in Table 1, whereas the coefficient of correlation in Table 2.

Table 1
Values of coal production, methane emission and methane drainage into the atmosphere from hard coal mines

Coal mine	Coal production [tone]	Absolute methane content [mln m^3/year]	Methane content in ventilation air [mln m^3/year]	Methane drainage [mln m^3/year]	Methane drainage efficiency [%]
Bielszowice	1016003	17.63	14.44	3.19	18.09
Budryk	2914221	146.62	77.72	68.9	47.06
Halemba	1322380	15.74	12.17	3.57	11.94
Knurów-Szczygłowice	3654331	57.64	29.18	28.46	49.38
Sośnica	864555	30.26	21.52	8.33	27.91
Pokój	754196	1.4	1.4	0	0
Bolesław Śmiały	917875	0.12	0.12	0	0
Brzeszcze	1031739	77.7	50.02	27.68	35.62
Silesia	1792200	38.1	19.92	18.18	47.72
Murcki-Staszic	3007550	43.35	28.76	14.59	33.66
Mysłowice-Wesoła	2923000	83.56	61.03	22.53	26.96
Wujek	2204000	22.81	11.91	10.9	47.79
Wieczorek	1345940	20.53	20.53	0	
Rydułtowy	1439830	27.08	18.43	8.65	32.88
Chwałowice	1749172	13.64	9.8	3.84	28.15
Jankowice	1525803	26.21	19.91	6.3	24.4
Marcel	1966200	20.73	14.96	5.77	27.83
Borynia-Zofiówka-Jastrzębie	5831310	99.97	68.16	31.81	31.82
Pniówek	3020193	103.96	69.96	34	32.7
Krupiński	1864999	74.94	27.87	47.07	62.81
Coefficient of variation, %	59.64	84.64	81.01	105.29	52.57

Source: own study based on (Patyńska, 2017).

The set of variables presented in Table 1 is characterised by significant dispersion of the coefficient of variation, ranging from 52.57% to 105.29%. Therefore, these variables meet the condition of diagnostic features. Moreover, an analysis of the correlation coefficient demonstrated that these variables have a different level of correlation.

Table 2
Results of statistical analysis (correlation matrix)

	Absolute methane content	Methane content in ventilation air	Methane drainage	Methane drainage efficiency
Absolute methane content	1	0.961898798	0.935272836	0.54934317
Methane content in ventilation air	0.961898798	1	0.802881773	0.400300539
Methane drainage	0.935272836	0.802881773	1	0.684560602
Methane drainage efficiency	0.54934317	0.400300539	0.684560602	1

The similarity assessment of the mines in terms of their methane hazard was also conducted with account being taken of their extraction volumes. It was therefore necessary to calculate the indicators presented in Table 1 per tonne of the coal extracted. Due to limitations of space, some of these data have not been included in the publication.

The *k-means* algorithm tries to find the objective function extreme value, which is defined by the following relationship (Everitt, 2011):

$$J = \sum_{i=1}^{k} \sum_{d_t \in D_i} sim(c_{i,} d_t) \quad (1)$$

where:

c is centroid of the set of objects "*D*".

The algorithm of the research procedure consists of the following seven stages:

1. Standardisation of the data applied for calculations, aimed at obtaining variables with a variance equal to 1 and a mean equal to 0:

$$U = \frac{x_i - \bar{x}}{S(x)} \tag{2}$$

where:

$\bar{x}$ is average, *S(x)* is standard deviation of the test variables.

2. A priori determination of the number of concentrations (*K*).
3. Assignment of measurement samples to the particular clusters on the basis of the determined Euclidean distances d_{ij} of the individual samples P_i from the clusters' centres m_i:

$$d_{ij} = \|x_j - m_i\| = \sqrt{\sum_{l=1}^{k} (x_{lj} - m_{xlj})^2} \tag{3}$$

4. Determination of new clusters' centres using the cumulative method is performed on the basis of the relationship:

$$m_{xl,i}(1) = \frac{1}{N_i} \sum_{j=1}^{N_i} x_{lj}(0) \tag{4}$$

5. Determination of cluster shifts Δm:

$$\Delta m = \|m_i(0) - m_i(1)\| \tag{5}$$

6. Assignment of measurement samples to new clusters
7. Determination of new clusters' centres.

3. RESULTS AND DISCUSSION

The analyses which served as the basis for identifying homogeneous mines in terms of methane quantities emitted into the natural environment and collected by methane extraction systems were conducted for two cases: with and without the extraction volume being taken into consideration. The purpose was to verify whether extraction volumes influence the grouping of the mines into homogeneous clusters. In both cases under analysis, the assumption was that the mines would be grouped into 4 clusters.

The first clusters' centres were determined on the basis of distance sorting. The resultant groups and the distances from the clusters' centres (without taking into account the amount of coal excavated) have been presented in Table 3.

Table 3
Elements (coal mines) of clusters with distances form centres for methane emission and methane drainage

Cluster 1 (distance from centre of cluster)	Cluster 2 (distance from centre of cluster)	Cluster 3 (distance from centre of cluster)	Cluster 4 (distance from centre of cluster)
Bielszowice (0.3772977)	Knurów-Szczygłowice (0.3409263)	Sośnica (0.190896)	Budryk (1.134807)
Halemba (0.1988936)	Krupiński (0.3409263)	Silesia (0.488109)	Brzeszcze (0.521594)
Pokój (0.280158)		Murcki-Staszic (0.331119)	Mysłowice-Wesoła (0.526359)
Bolesław Śmiały (0.3053222)		Wujek (0.433377)	Borynia-Zofiówka Jastrzębie (0.180319)
Wieczorek (0.3150994)		Rydułtowy (0.038193)	Pniówek (0.143567)
		Chwałowice (0.3402644)	
		Jankowice (0.290062)	
		Marcel (0.231378)	

The most similar mines in terms of the methane-bearing capacity and the volume of demethylation are those in cluster 1 (Bielszowice, Halemba, Pokój, Bolesław Śmiały, Wieczorek), because their distances from the cluster's centre exhibit the smallest differences. On the other hand, the mines in cluster 5 exhibit the greatest differences between each other in terms of the values under analysis, because they lie the farthest from the cluster's centre. The average values of the absolute methane-bearing capacity and ventilation methane-bearing capacity as well as of the demethylation and its effectiveness by the mines in the particular clusters have been presented in Table 4.
The data presented unambiguously indicate that the greatest explosion hazard is present in the mines/mining enterprises in cluster 4 (Budryk, Brzeszcze, Mysłowice-Wesoła, Borynia-Zofiówka-Jastrzębie, Pniówek), whereas the smallest in cluster 1 (Bielszowice, Halemba, Pokój, Bolesław Śmiały and Wieczorek).
Figure 1 presents a diagram with the distribution of mines in a two-dimensional space for the variables that have a decisive impact on the formation of the clusters.

Table 4
Average total emissions of methane and methane drainage in clusters

	Absolute methane content [mln m^3/year]	Methane content in ventilation air [mln m^3/year]	Methane drainage [mln m^3/year]	Methane drainage efficiency [%]
Cluster 1	11.08	9.73	1.35	7.51
Cluster 2	66.29	28.53	37.77	56.10
Cluster 3	27.77	18.15	9.57	33.79
Cluster 4	102.36	65.38	36.98	34.83

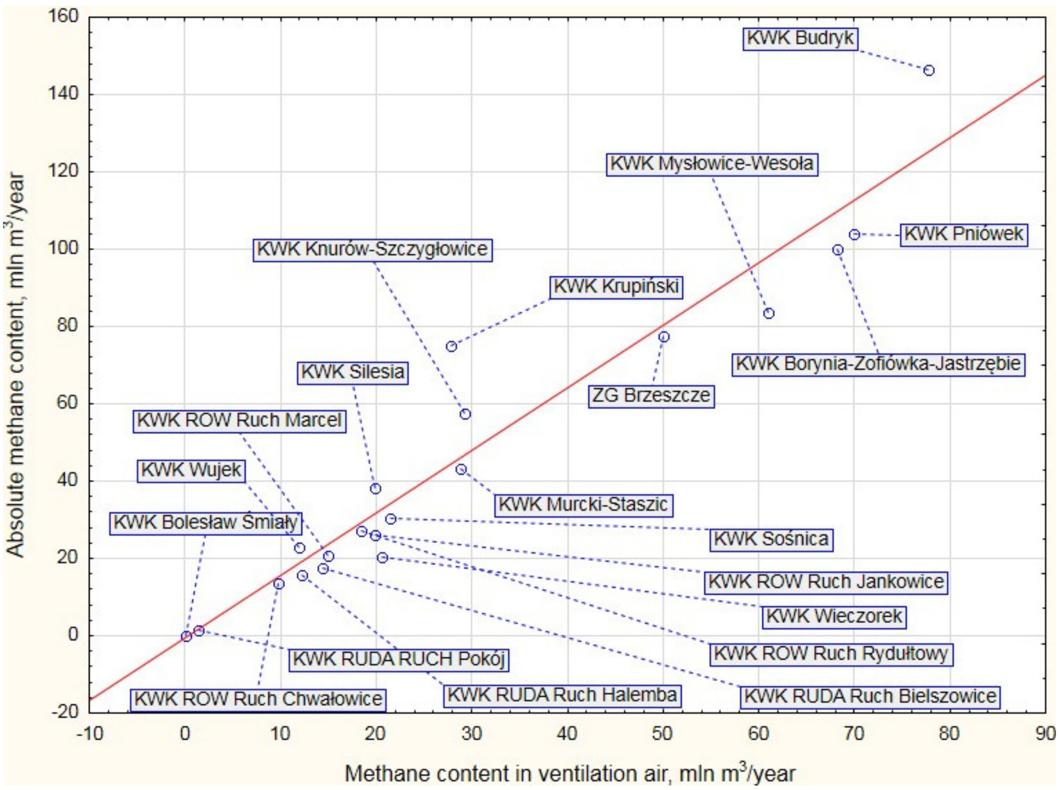

Fig. 1. Mine dispersion in a two-dimensional space for variable absolute methane content and methane content in ventilation air

The next stage involved grouping of the mines with account being taken of their extraction volumes. However, due to limitations of space, below there are only the compositions of the particular clusters (table 5). Figure 2 presents a diagram with the distribution of mines in a two-dimensional space for the variables that have a decisive impact on the formation of these clusters.

Table 5
Elements of clusters with distances form centres for methane emission and methane drainage per tonne of coal

Cluster 1 (distance from centre of cluster)	Cluster 2 (distance from centre of cluster)	Cluster 3 (distance from centre of cluster)	Cluster 4 (distance from centre of cluster)
Bielszowice (0.252429)	Sośnica (0.708205)	Budryk (0.609766)	Halemba (0.312021)
Knurów-Szczygłowice (0.272968)	Mysłowice-Wesoła (0.430468)	Brzeszcze (1.070392)	Pokój (0.376735)
KWK Silesia (0.551306)	Pniówek (0.334202)	Krupiński (0.859019)	Bolesław Śmiały (0.465265)
Murcki-Staszic (0.309590)			Wieczorek (0.427689)
Wujek (0.300265)			Borynia-Zofiówka-Jastrzębie (0.393621)
Rydułtowy (0.303392)			
Chwałowice (0.336300)			
Jankowice (0.196099)			
Marcel (0.266215)			

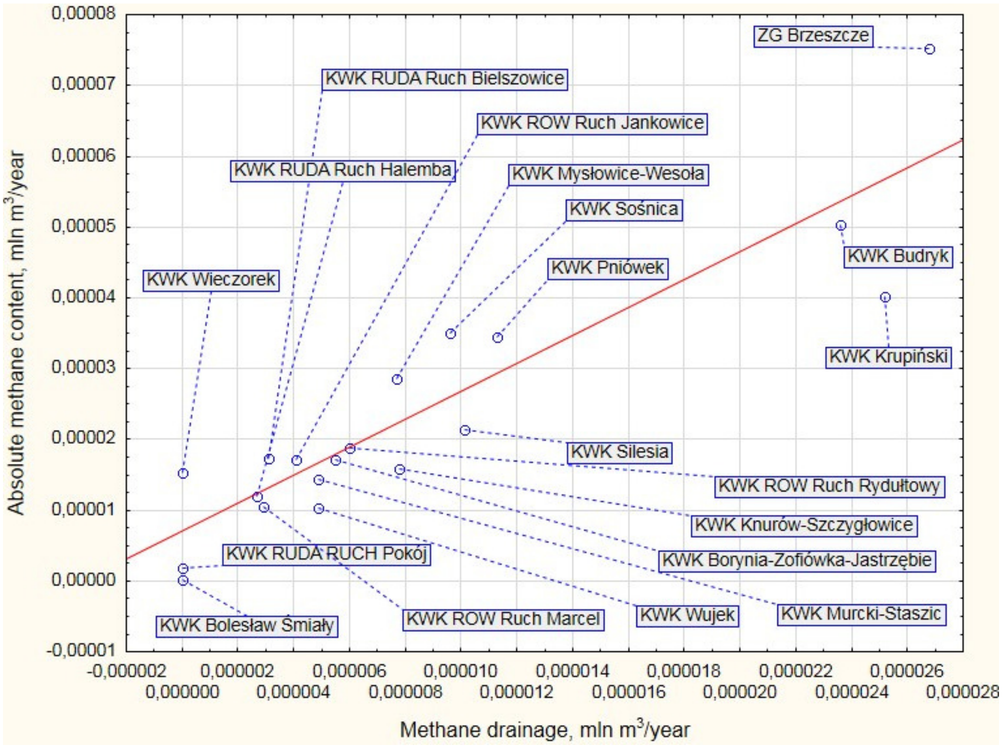

Fig. 2. Mine dispersion in a two-dimensional space for methane drainage and absolute methane content

4. CONCLUSION

One of the most dangerous and widespread risks in hard coal mines is the methane hazard. It is related to the potential ignition and/or explosion of methane in the mixture with air. Besides posing a threat to safety of work and disrupting the production process, methane released from mines also represents a major risk to the natural environment. This is due to the permeation of large quantities of this gas into the environment through the ventilation systems present in mines. The magnitude of these risks is determined by the amount of methane emitted into the mine's atmosphere during mining works as well as by the amount of methane collected by methane drainage systems.

In order to enhance the effectiveness of the measures aimed at limiting the negative environmental footprint of methane and improving the safety of work, the mines were grouped into clusters of similar features. This process was performed on the basis of algorithms for non-hierarchical analysis of clusters. The purpose of these activities was to combine the mines with similar levels of methane hazard. The Author assumes that this information will encourage the mines to cooperate with each other, exchange their experiences and develop a common preventive and business action plan in terms of methane management. In both cases, the results demonstrate the great diversity of Polish mines in this regard. The level of methane hazard in the particular mines varies significantly. This variation is affected not only by the total amount of emitted and collected methane, but also by the extraction volume. It should also be stated that for many mines the indicators are very similar. This area offers an opportunity for closer cooperation.

The results obtained provide more in-depth knowledge on the methane hazard in hard coal mining. They also show the seriousness of this problem for the natural environment and the work safety in mines. On the one hand, methane is a very dangerous gas. On the other, it makes a good energy raw material, which provides mines with the opportunity to enhance their economic effectiveness. It is therefore necessary to take various types of actions aimed at minimising the negative environmental footprint of methane and improving the safety of mining operations

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