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CRITERIA OF GRAHAM'S RATIO APPLICATION IN AREAS SUBJECTED TO NITROGEN INERTISATION

The introduction of the article presents the problem of interpreting the level of fire hazard basing on Graham's ratio, which, in certain ranges of the value of its denominator, may be wrong. The range of credibility for the index is also discussed. The issue of nitrogen inertisation and its influence on the value of the discussed index is also addressed. To determine the influence, two statistical samples were set. They consisted of the results of precise chromatographic analyses of the air samples collected in the longwall areas which were not subjected to inertisation and in the areas where nitrogen was applied as the inert gas. Then, with Student's t-test, there was conducted a comparative analysis of both groups with regard to the equality of the average concentrations of gases emitted in the coal self-heating process. At the end, there were developed criteria for the application of Graham's ratio for the air samples of the increased content of nitrogen, which, according to the discussed index, did not indicate the occurrence of an endogenous fire hazard.

Keywords: mining industry, fire hazard, inertisation, Graham's ratio

1. Introduction

The ventilation personnel of hard coal mines employ various fire indices while assessing the level of endogenous fire hazard occurring in the exploitation areas. In Poland, the most commonly used one is Graham's ratio which is dedicated for fire hazard assessment in the measuring points located in goafs and behind the barriers by the Regulation of the Minister of Energy (2016).

Graham's ratio was developed almost a hundred years ago when nitrogen was not applied yet to inert the areas with self-heating coal. Nowadays, when nitrogen inertisation is one of the basic means of fire prevention, it is sometimes difficult to assess the level of fire hazard unambigu-

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ously, basing on the aforementioned index. It is so, because nitrogen occurs in the denominator of the dependence serving to determine the values of Graham's ratio. That is why any increased concentration of nitrogen (e.g. from inertisation) may result in anomalous (lowered) value of the discussed index.

The article presents an analysis of the influence of increased concentrations of nitrogen on the value of Graham's ratio. There is also developed criterion, which is advised to apply in a situation when, according to the discussed index, the air samples collected from the places subjected to nitrogen inertisation do not indicate endogenous fire hazard.

2. Credibility range of Graham's ratio

In accordance with Polish regulations (Regulation of the Minister of Energy, 2016) Graham's ratio is determined with the following equation:

$$G = \frac{CO}{0,265 \cdot N_2 - O_2} \tag{1}$$

where:

CO — concentration of carbon oxide [%],

N_2 — concentration of nitrogen [%],

O_2 — concentration of oxygen [%].

The dependence (1) presents the ratio of the concentration of carbon oxide to the oxygen loss, while the oxygen loss is calculated in reference to the fresh air in which the proportion of oxygen to nitrogen is 0.265. The analysis of the equation (1) shows that Graham's ratio may asymptotically approach either zero or infinity. It results from its mathematical structure and depends on the value of its denominator. In practice it is observed that, in certain ranges of values of the denominator, the interpretation of fire hazard according to Graham's ratio does not reflect the actual fire situation.

In the literature, there are publications which consider the very low values of the denominator of the index, resulting in wrongly generated high levels of fire hazard. For example MacKenzie-Wood and Strang (1990) reported that if the oxygen loss is lower than 0.2 it is necessary to be careful while interpreting such results due to serious errors. Mitchell (1996) and Brady (2007, 2008) also observed that, when the oxygen loss is lower than 0.3 Graham's ratio may be unreliable. However, Muller, Ryan, Hollyer and Bajic (2017) think that the minimal oxygen loss for the index ought to be within the range between 0.1 and 0.3 because discarding all the cases lower than 0.3 may result in losing potentially significant results.

In turn, Trenczek (2003) concluded that if the gases collected from a fire hazard area are diluted with inert gas (e.g. nitrogen), the obtained results may make it harder or even render it impossible to assess the actual level of endogenous fire hazard. According to him, if inert gases flow to a measuring point bypassing the coal self-heating area, then the assessment of the fire hazard level, according to Graham's ratio, is insufficient.

Słowik and Świerczek (2014, 2015) treated the dependence (1), applied to determine the value of Graham's ratio, as a hyperbolic function. During analyses, they considered values of the function in the first quarter of the coordinate system (for $x > 0$ and $y > 0$). By employing the properties of the hyperbola, they showed that Graham's ratio may increase the level of endogenous fire hazard when the denominator reaches low values; but there may also be situations when the index lowers the hazard level when the value of the denominator is high. By applying proper mathematical tools, they determined the range of credibility for the index. According to them, if the value of the denominator of Graham's ratio is within the range of $0.2 < (0.265 \times N_2 - O_2) < 5.7$ then, with 95% probability, it may be assumed that Graham's ratio generates reliable values. Outside the range it is not certain and it is advised to apply other tools while assessing the level of endogenous fire hazard.

3. Preparation of data for a comparative analysis of the air samples

Different countries have different regulations regarding the interpretation of fire hazard levels, according to the Graham's ratio, and different ways of responding to this hazard. Because the research was carried out in Poland, therefore it was based on the Polish criteria for this ratio. Following the Polish regulations (Regulation of the Minister of Energy, 2016), the fire hazard and the corresponding action levels are characterized (according to the Graham's ratio) by the following criteria:

- $0 < G \leq 0.0025$ – the situation is normal – there is no hazard in the goafs,
- $0.0025 < G \leq 0.0070$ – increased observation of the atmosphere in the goafs and more frequent collections of the air samples are necessary,
- $0.0070 < G \leq 0.0300$ – it is necessary to start works aimed at eliminating or limiting the hazard while maintaining normal operations in the area; the schedule of the works is prepared by the head of the ventilation department and approved by the head of the mining facility,
- $G > 0.0300$ – it is necessary to initiate a fire-fighting action.

The possibility that Graham's ratio may lower the level of fire hazard is highly unfavourable. Such a situation may result in a false sense of security, which in turn, may result in erroneous decisions taken by the personnel responsible for fighting the hazard in underground mines. The least desirable case is the one in which Graham's ratio would wrongly consider a given air sample as the normal situation, while in fact, it would represent a much higher level of hazard. Hence, further analyses will focus only on the air samples with the values of Graham's ratio within the range between 0 and 0.0025. Following the Polish regulations (Regulation of the Minister of Energy, 2016), such air samples do not indicate endogenous fire hazard (the normal situation).

To verify if the air samples collected from the longwall areas subjected to inertisation were, according to Graham's ratio, correctly considered as the normal situation (with no fire hazard), it was decided to conduct a comparative analysis of the concentrations of essential gases emitted in the process of coal self-heating (i.e. such gases as: ethylene, propylene, acetylene, carbon oxide and hydrogen). The analysis was to show if there are significant differences in the average concentrations of the aforementioned gases between the samples collected in the areas which are not subjected to inertisation and the ones collected in the areas where nitrogen is applied as the inert gas. It is obvious that, if Graham's ratio correctly determines the level of fire hazard as the normal situation, then in both cases the concentrations of ethylene, propylene, acetylene, carbon oxide and hydrogen ought to be at a similarly low level.

Two groups were created for the analyses. They consisted of the results of precise chromatographic analyses of the air samples. One contained the air samples collected from the longwall goafs and from behind the barriers, where nitrogen was not applied as the inert gas – hereinafter referred to as Group I. The other group consisted of the air samples collected in similar places but of increased concentrations of nitrogen, associated with the application of inertisation – hereinafter referred to as Group II.

3.1. Statistical sample consisting of air samples with nitrogen concentration lower than 80% – Group I

To determine the statistical sample, a vast data base of the results of chromatographic analyses of the air samples collected from different mining areas in hard coal mines was applied. With proper queries in Structured Query Language (SQL) only the air samples which met the following conditions were selected:

- the air samples were collected from the longwall goafs or from behind the barriers – according to the Polish regulations (Regulation of the Minister of Energy, 2016) in this places it is necessary to determine the value of Graham's ratio,
- concentration of nitrogen in the samples was lower than 80%, because higher concentrations of the gas are observed at the initial stage of inertisation,
- values of Graham's ratio for the samples fell in the range of $0 < G \leq 0.0025$ – according to the Polish regulations (Regulation of the Minister of Energy, 2016) the samples indicate the normal situation (with no fire hazard),
- values of the denominator of the index belonged to the range of $0.2 < (0.265 \times N_2 - O_2) < 5.7$ – according to Słowik and Świerczek (2015), with 95% probability, it means credible values of Graham's ratio.

Table 1 presents descriptive statistics of a statistical sample prepared in such a way.

TABLE 1

Descriptive statistics determined for the cases when the concentration of nitrogen was lower than 80%

Variable	Descriptive statistics						
	Valid N	Average	Minimum	Maximum	Percentile 90	Standard Deviation	Skewness
Ethylene [ppm]	9624	0.674	0.01	155.00	0.14	8.205	15.056
Propylene [ppm]	9624	0.133	0.01	18.80	0.16	0.943	15.016
Acetylene [ppm]	9624	0.0118	0.001	3.450	0.011	0.089	20.348
Carbon oxide [ppm]	9624	10.517	1	138	27	15.274	3.078
Oxygen [%]	9624	18.116	0.06	20.78	20.72	4.320	–2.724
Nitrogen [%]	9624	74.160	3.05	79.99	79.52	13.343	–3.612
Carbon dioxide [%]	9624	1.019	0.05	89.03	2.05	4.914	14.976
Methane [%]	9624	6.687	0.00	96.12	14.15	16.454	3.674
Hydrogen [ppm]	9624	20.518	0.4	5700.0	41.6	96.910	31.773
Graham's ratio	9624	0.00077	0.00002	0.00250	0.00175	0.00062	0.932
Denominator of Graham's ratio	9624	1.536	0.20	5.70	4.07	1.473	1.223

The analyses of the descriptive statistics, presented in Table 1 show that the concentrations of gases contained in the selected air samples were significantly different than the normal distribution – it may be observed in the high values of skewness, which is the measure of an asymmetric distribution. Hence, in the statistical samples, the outlying elements were marked and then discarded with the three-sigma rule. It means that all the cases in which the concentrations of the essential gases were beyond the threshold of three standard deviations, calculated on the basis of the average values, were discarded. The descriptive statistics for the statistical samples prepared in such a way are presented in Table 2.

TABLE 2

Statistical samples determined for air samples containing the concentration of nitrogen lower than 80% – after discarding the outliers (Group I)

Variable	Descriptive statistics						
	Valid N	**Average**	**Minimum**	**Maximum**	**Percentile 90**	**Standard Deviation**	**Skewness**
Ethylene [ppm]	8462	0.036	0.01	0.12	0.08	0.028	1.263
Propylene [ppm]	7985	0.029	0.01	0.10	0.07	0.024	1.367
Acetylene [ppm]	8356	0.0026	0.001	0.008	0.005	0.002	1.250
Carbon oxide [ppm]	8355	5.706	1	22	14	5.437	1.296
Hydrogen [ppm]	6958	3.260	0.4	11.0	7.4	2.582	1.159

Table 2 contains the descriptive statistics of the concentrations of the essential gases, which are emitted during the process of coal self-heating, in the air samples collected from the areas which were not subjected to nitrogen inertisation. The presented gases form Group I, which was used for further analyses. The presented table shows that discarding the outlying elements significantly decreased skewness in all the presented cases. Hence, their distributions approached significantly the normal distribution.

The average values of the concentrations of the essential gases emitted during the coal self-heating process (ethylene, propylene, acetylene, carbon oxide and hydrogen) in Group I did not show any signs of an increased level of endogenous fire hazard (Cygankiewicz, 1996; Trenczek, 2003, 2010).

3.2. Statistical sample consisting of the air samples with nitrogen concentration greater than or equal to 80% – Group II

To determine a statistical sample consisting of the concentrations of gases in the air samples collected in the areas subjected to nitrogen inertisation, the same data base was used as for the determination of the air samples forming Group I. In the select query was just marked the condition that the concentration of nitrogen ought to be greater than or equal to 80%. The descriptive statistics of the sample formed in such a way are presented in Table 3.

Like in Group I, there may be observed significant skewness of the concentrations of the presented gases, which indicates highly asymmetrical distribution of the analysed cases. Hence, they were also analysed with regard to the occurrence of the outlying elements. The three-sigma rule was applied again, and the descriptive statistics for the air samples remaining after discarding the outliers are presented in Table 4.

TABLE 3

Descriptive statistics determined for the cases in which the concentration of nitrogen was greater than or equal to 80%

Variable	Descriptive statistics						
	Valid N	**Average**	**Minimum**	**Maximum**	**Percentile 90**	**Standard deviation**	**Skewness**
Ethylene [ppm]	2661	0.080	0.01	8.27	0.13	0.244	21.261
Propylene [ppm]	2661	0.064	0.01	2.80	0.12	0.127	11.699
Acetylene [ppm]	2661	0.0146	0.001	1.510	0.023	0.062	13.840
Carbon oxide [ppm]	2661	17.902	1	130	54	23.688	1.767
Oxygen [%]	2661	17.956	15.57	19.88	19.29	1.004	-0.064
Nitrogen [%]	2661	81.128	80.00	83.24	82.34	0.805	0.475
Carbon dioxide [%]	2661	0.661	0.04	4.00	1.46	0.553	1.365
Methane [%]	2661	0.251	0.00	3.71	0.80	0.435	2.617
Hydrogen [ppm]	2661	39.273	0.5	1860.0	101.0	129.841	6.761
Graham's ratio	2661	0.00055	0.00002	0.00250	0.00171	0.00068	1.280
Denominator of Graham's ratio	2661	3.543	1.33	5.70	5.19	1.173	0.045

TABLE 4

Statistical sample determined for the air samples of nitrogen concentration greater than or equal to 80% – after discarding the outliers (Group II)

Variable	Descriptive statistics						
	Valid N	**Average**	**Minimum**	**Maximum**	**Percentile 90**	**Standard Deviation**	**Skewness**
Ethylene [ppm]	2549	0.057	0.01	0.17	0.11	0.039	0.628
Propylene [ppm]	2436	0.041	0.01	0.13	0.08	0.030	1.010
Acetylene [ppm]	2110	0.0031	0.001	0.010	0.007	0.002	1.215
Carbon oxide[ppm]	2462	12.891	1	60	39	15.739	1.345
Hydrogen [ppm]	1943	2.965	0.5	11.1	7.5	2.720	1.217

Table 4 shows the descriptive statistics of the concentrations of the essential gases, which are emitted during the coal self-heating process, contained in the air samples collected in the areas subjected to nitrogen inertisation. The cases form Group II, which was used for further analyses. Discarding the outliers, like in Group I, decreased skewness of all the analysed gases, and their distribution approached the normal distribution.

The analysis of descriptive statistics in Table 4 shows that the average concentrations of the essential gases, emitted during the coal self-heating process, did not show any signs of an increased level of fire hazard (Cygankiewicz, 1996; Trenczek, 2003, 2010). Yet, it may be observed that the average concentrations of gases from Group II, except the concentration of hydrogen, were higher than the values of their counterparts in Group I.

4. Comparative analysis of the air samples

To compare the prepared statistical samples (Group I vs. Group II) with regard to the equality of the average concentrations of the essential gases, it was decided to apply Student's t-test for independent samples. The test is applied to check if there are significant differences between two independent groups. By applying the test, it is possible to determine, with at least 95% probability, if there are grounds to discard the null hypothesis, which states there are no differences between the average values.

As it is a parametric test, to apply it, there must be met the assumption concerning normality of the distribution of the tested qualities. In our case, the groups had very high cardinality (the lowest cardinality was 1943 for the concentrations of hydrogen in Group II), which enabled application of the Central Limit Theorem (CLT). According to the theorem, as the number of samples increases, the distribution of the average values approaches the normal distribution. Most researchers dealing with statistics think that if the cardinality is greater than 30 then, by applying the Central Limit Theorem, it may be assumed that the analysed variable has a roughly normal distribution (Hogg et al., 2015).

Then it was necessary to determine if the assumption of homogeneity of variances in both groups is met. If the assumption is met, then to verify the equality of the average values in two groups, Student's t-test for homogeneous variances is applied. In other cases, it is necessary to apply Cochran-Cox test i.e. Student's t-test for the heterogeneous variances. Table 5 presents the results of: F-test, Levene's test, Brown-Forsythe test, which were applied to check the assumptions of homogeneity of the variances in the tested groups. If the probability value for the tests exceeds the materiality threshold of 0.05 it means there are no grounds to discard the null hypothesis concerning the equality of the variances.

The results of the conducted tests (Table 5) showed that in case of all the analysed gases the value of probability (p) was much lower than the statistical significance of 0.05. Hence, for the groups, it was necessary to discard the null hypothesis of homogeneity of variances of the corresponding gases. Thus, while checking the equality of the average values in the groups, it was necessary to apply Cochran-Cox test – for the heterogeneous variances.

Then, with Student's t-test for the heterogeneous variances, it was checked if the average concentrations of the gases emitted during the coal self-heating process in Group I are equal to their counterparts in Group II. It was assumed that if Graham's ratio correctly considered air samples, of increased concentrations of nitrogen (Group II), as the normal situation (no endogenous fire hazard), the average concentrations of essential gases ought to be at a similar level to the concentrations of their counterparts in the air samples with no increased concentrations of nitrogen (Group I). The results of the conducted tests are presented in Table 6.

Analyzing the results of the conducted tests (Table 6), it may be concluded that for all the aforementioned gases the value of probability (p) for a heterogeneous variance (in Cochran-Cox test) was close to 0. Hence, the null hypothesis was discarded (regarding the equality of the average values in the compared groups) for an alternative hypothesis concerning lack of equality of the analysed average values.

It means that, in spite of the fact that Graham's ratio considers the air samples forming both tested groups as the normal situation, there are significant differences between the groups at the average concentrations of the corresponding gases. The average concentrations of ethylene, propylene, acetylene and carbon oxide in Group II were higher than in Group I. It implies that

TABLE 5

Results of the tests verifying homogeneity of variances in the tested statistical samples (Group I vs. Group II)

Group I vs. Group II	Valid N Group 1	Valid N Group 2	Quotient F variances	p variances	Levene's F(1, df)	p Levene's	Brown-Forsythe F(1, df)	p Brown-Forsythe
Ethylene – group I vs. Ethylene – group II	8462	2549	2	0.000	638.95	0.000	598.20	0.000
Propylene – group I vs. Propylene – group II	7985	2436	2	0.000	200.26	0.000	216.50	0.000
Acetylene – group I vs. Acetylene – group II	8356	2110	2	0.000	185.83	0.000	123.00	0.000
Carbon oxide – group I vs. Carbon oxide – group II	8355	2462	8	0.000	4814.50	0.000	1661.24	0.000
Hydrogen – group I vs. Hydrogen – group II	6958	1943	1	0.004	6.62	0.010	5.20	0.023

TABLE 6

Results of Student's t-tests comparing the equality of the average concentrations of gases (Group I vs. Group II)

Group I vs. Group II	Average Group I	Average Group II	t for homogeneous variances	df	p for homogeneous variances	t for heterogeneous variance	df	p for heterogeneous variance
Ethylene – group I vs. Etalon – group II	0.0357	0.0569	–30.220	11009	0.0000	–25.351	3368.43	0.0000
Propylene – group I vs. Propylene – group II	0.0293	0.0415	–20.912	10419	0.0000	–18.568	3432.88	0.0000
Acetylene – group I vs. Acetylene – group II	0.0026	0.0031	–11.114	10464	0.0000	–9.604	2790.95	0.0000
Carbon oxide – group I vs. Carbon oxide – group II	5.7064	12.8907	–35.203	10815	0.0000	–22.262	2636.20	0.0000
Hydrogen – group I vs. Hydrogen – group II	3.2601	2.9648	4.405	8899	0.0000	4.278	2989.15	0.0000

the level of fire hazard represented by the air samples collected from the areas where nitrogen is applied as the inert gas, was probably higher than the one determined with Graham's ratio. Such a situation occurred in spite of the fact that the credibility criterion was applied (while creating both groups) for the index presented by Słowik and Świerczek (2015). It may be then concluded that the aforementioned criterion, which recommends not applying Graham's ratio if the value of its denominator does not fit within the range of $0.2 < (0.265 \times N_2 - O_2) < 5.7$ was insufficient in case of the air samples with increased concentrations of nitrogen.

5. Determination of the additional conditions for applying Graham's ratio in the areas subjected to nitrogen inertisation

As it was mentioned, the basic criterion which was applied while forming comparable statistical samples (Group I and Group II) was the credibility criterion of Graham's ratio, presented by Słowik and Świerczek (2015). Nevertheless, it was demonstrated that, in case of the nitrogen inertisation this criterion is insufficient to recognise correctly endogenous fire hazard according to Graham's ratio and it ought to be supplemented with additional condition. It was assumed that such condition may be introduced basing on the concentrations of the essential gases emitted during the coal self-heating process (ethylene, propylene, acetylene, carbon oxide and hydrogen).

It was decided then to check if it is possible to determine the threshold concentrations of the essential gases in Group II, for which the average concentrations of the gases in both groups would be at the same level. Reaching the equality was a prerequisite to confirm the same level of fire hazard occurring in both compared cases. The average concentration of hydrogen was not considered any further as the concentration in Group II was lower than in Group I (Table 6). Hence, it could not be used to verify the proper classification of the fire hazard level with Graham's ratio in the areas inerted with nitrogen.

In the further analyses, the threshold of the concentration of ethylene, propylene, acetylene and carbon oxide was lowered in Group II and then compared with Group I. As the threshold descended, the elements of Group II which exceeded it were discarded. The operation was continued until Student's t-test showed that the average values of the concentrations of comparable gases in both groups were equal. In this way, the threshold concentrations of essential gases in Group II were determined, which ought not be exceeded in order to be able to claim (with at least 95% certainty level) that the air samples collected from the areas subjected to nitrogen inertisation (Group II) were correctly considered, according to Graham's ratio, as the normal situation (no endogenous fire hazard). It is necessary to mention that Statistica software selected proper Student's t-tests itself, depending on the cardinality of the tested groups and the results of the tests for homogeneity of variances in the analysed groups. The results of the conducted analyses are presented in Table 7. Additionally, Figures 1, 2, 3 and 4 show graphic interpretation of the obtained results in form of box and whisker plots.

Basing on the results of the analyses in Table 7 it may be concluded that discarding the cases which exceed the concentration of 0.08 ppm for ethylene, 0.07 ppm for propylene, 0.008 ppm for acetylene and 25 ppm for carbon oxide from Group II, further differentiated the analyzed groups in such a way that it was impossible (with the acceptable level of certainty) to assume the null hypothesis, which states there are no differences between the average concentrations of corresponding gases.

TABLE 7

Results of comparison of average concentrations of essential gases during discarding ever lower concentrations from Group II

Group I vs. Group II	Average Group I	Average Group II	t for homogen. variances	df	p for homogen. variances	t for heterogen. variances	df	p for heterogen. variances
Ethylene - group I vs. Ethylene - group II (discarded concentrations of ethylene > 0.08 ppm)	0.0357	0.0392	-4.975	10395	0.0000	-5.487	3260.69	0.0000
Ethylene - group I vs. Ethylene - group II (discarded concentrations of ethylene > 0.07 ppm)	0.0357	0.0347	1.461	10204	0.1440	1.769	3189.53	0.0770
Propylene - group I vs. Propylene - group II (discarded concentrations of propylene > 0.07 ppm)	0.0293	0.0321	-4.989	10073	0.0000	-5.684	3982.09	0.0000
Propylene - group I vs. Propylene - group II (discarded concentrations of propylene > 0.06 ppm)	0.0293	0.0295	-0.367	9940	0.7136	-0.452	4132.31	0.6511
Acetylene - group I vs. Acetylene - group II (discarded concentrations of acetylene > 0.008 ppm)	0.0026	0.0028	-4.645	10363	0.0000	-4.500	2939.92	0.0000
Acetylene - group I vs. Acetylene - group II (discarded concentrations of acetylene > 0.007 ppm)	0.0026	0.0026	-1.058	10301	0.2903	-1.100	3063.32	0.2712
Carbon oxide - group I vs. Carbon oxide - group II (discarded concentrations of carbon oxide > 25 ppm)	5.7064	6.1318	-2.947	10333	0.0032	-2.521	2568.03	0.0118
Carbon oxide - group I vs. Carbon oxide - group II (discarded concentrations of carbon oxide > 24 ppm)	5.7064	5.8612	-1.080	10305	0.2800	-0.950	2582.89	0.3423

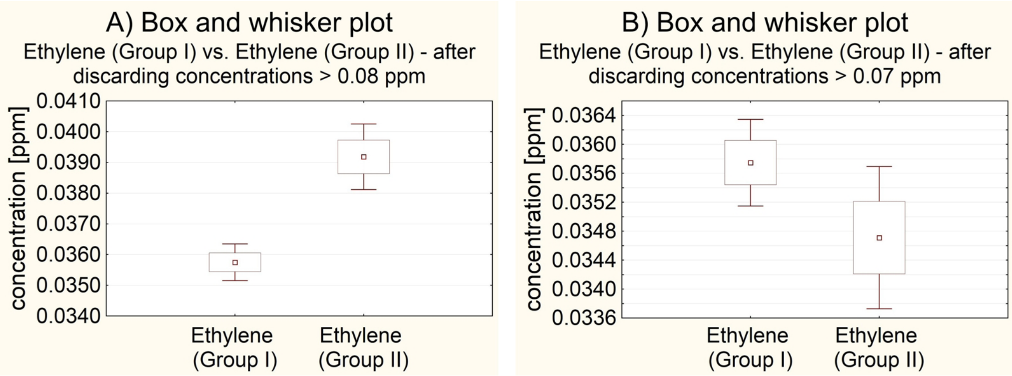

Fig. 1. Graphic interpretation of the comparison of the average concentrations of ethylene in both groups during discarding concentrations of the gas which exceed descending thresholds in Group II

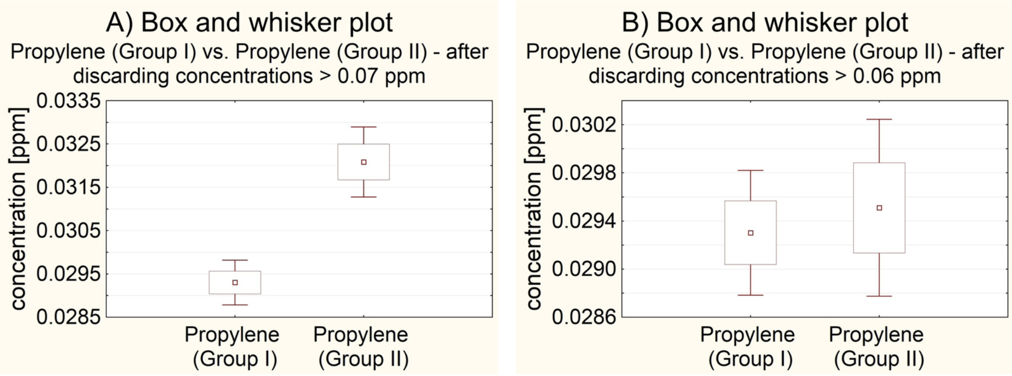

Fig. 2. Graphic interpretation of the comparison of the average concentrations of propylene in both groups during discarding concentrations of the gas which exceed descending thresholds in Group II

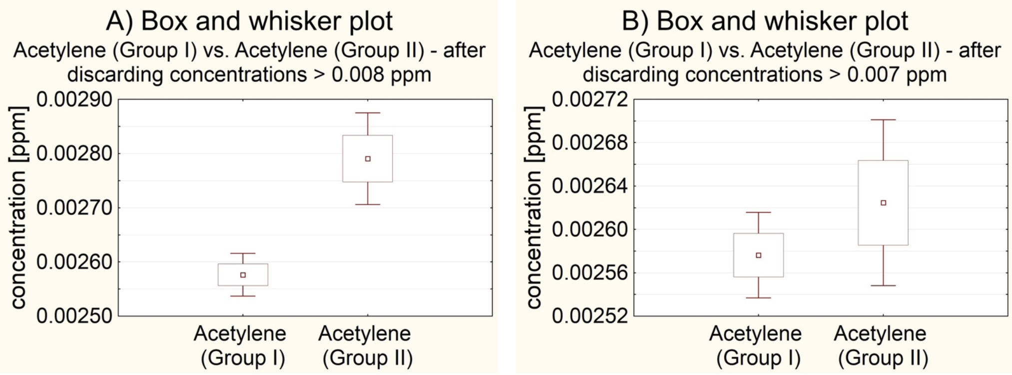

Fig. 3. Graphic interpretation of the comparison of the average concentrations of acetylene in both groups during discarding concentrations of the gas which exceed descending thresholds in Group II

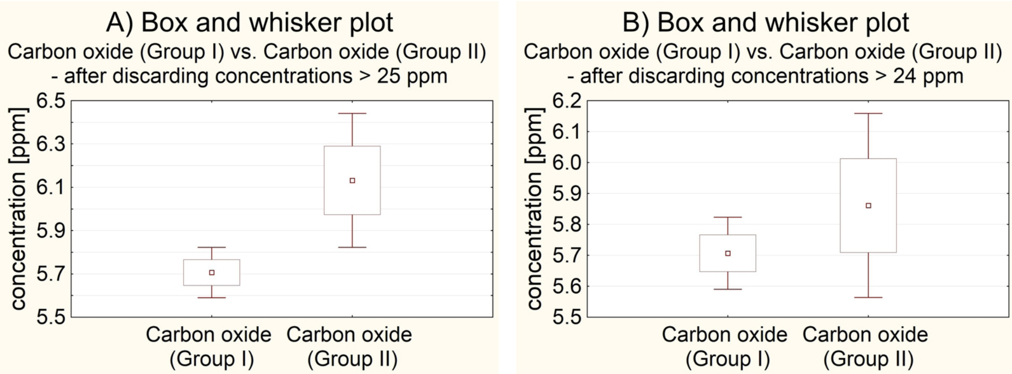

Fig. 4. Graphic interpretation of the comparison of the average concentrations of carbon oxide in both groups during discarding the concentrations of the gas which exceed descending thresholds in Group II

Lowering the threshold of the concentrations in Group II and discarding the cases which exceeded the concentration of 0.07 ppm for ethylene, 0.06 ppm for propylene, 0.007 ppm for acetylene and 24 ppm for carbon oxide enabled, with the 95% probability, a conclusion that between Groups I and II there are no significant differences in the average concentrations of corresponding gases. It means that the fire hazard represented by the air samples from Group II, modified in such a way, may be treated as the ones corresponding the conditions of Group I, i.e. the normal situation according to Graham's ratio.

Graphic interpretation of the comparison of the average concentrations of the gases in both groups (Figures 1, 2, 3 and 4) confirmed the results obtained from the conducted tests. In the presented figures the central box represents the average concentration of gases, while the thin lines (so-called whiskers) indicate 95% confidence limit of a given average. If the whiskers do not overlap (as it happened in all the cases marked "A"), it was necessary to discard the null hypothesis of the equality of the average values in the compared groups. In the cases marked "B" for ethylene and acetylene, the ranges of confidence limits overlap. For propylene and carbon oxide, the ranges of Group I were fully contained within the confidence limits determined for Group II. Hence, the cases marked with letter "B" confirm that there are no grounds for discarding the null hypothesis, which concerns the equality of the average values in the compared groups.

The conducted analyses show that if the air samples (containing nitrogen in an amount greater than or equal to 80%) were considered, according to Graham's ratio, as the normal situation (no endogenous fire hazard), the values of the index were credible (Słowik & Świerczek, 2015) and the concentrations of ethylene in the samples did not exceed 0.07 ppm, propylene – 0.06 ppm, acetylene – 0.007 ppm, and carbon oxide – 24 ppm, then the level of endogenous fire hazard, determined according to Graham's ratio (at 95% probability level), would be correct.

6. Summary

While interpreting the results of the early detection of endogenous fires in the exploitation areas of hard coal mines, it is possible to encounter cases in which correct assessment of the level of endogenous fire hazard, based on the value of Graham's ratio, is difficult. The value of the denominator of the index, which depends on the concentrations of nitrogen and oxygen in the collected air samples, directly affects it. The mathematical analysis of the equation applied to determine the value of Graham's ratio shows that the increased concentrations of nitrogen lower the value of the indicator. It is highly unfavourable situation because it may lead to drawing wrong conclusions concerning the fire situation. One of the worst scenarios would be the case of Graham's ratio indicating the normal situation, with a higher actual level of fire hazard.

The cases of surplus nitrogen appearing in the results of chemical analyses showed that the average concentrations of ethylene, propylene, acetylene and carbon oxide in the air samples from the areas subjected to nitrogen inertisation were higher than their counterparts in the air samples collected from places where inertisation was not applied. The inequality occurred in spite of the fact that the values of Graham's ratio suggested in both cases that the situation was normal. It means that the air samples collected from the longwall areas, where nitrogen was applied as the inert gas, probably represented higher level of hazard than the determined values of Graham's ratio actually showed it.

For the air samples from the mining areas where nitrogen is applied as the inert gas – in spite of the fact they meet the credibility criterion of Graham's ratio, provided by Słowik and Świerczek (2015) – it was necessary to develop additional condition to apply Graham's ratio. The condition was formulated employing the concentrations of gases emitted during the coal self-heating process. Applying Student's t-test, it was shown that, if the concentration of ethylene $\leq$ 0.07 ppm, propylene $\leq$ 0.06 ppm, acetylene $\leq$ 0.007 ppm and carbon oxide $\leq$ 24 ppm, then it may be concluded that Graham's ratio correctly considers air samples of the increased content of nitrogen as the normal situation (no endogenous fire hazard).

The given condition can also be used in other countries, where mining regulations categorize the fire hazard according to the Graham's ratio in a different way than specified in the article. To apply it, it is necessary to take into account cases, where the Graham's ratio does not indicate a fire hazard and the concentration of nitrogen in the air sample is greater than or equal to 80%.

If Graham's ratio considers an air sample as the normal situation (no endogenous fire hazard), and the content of nitrogen in the sample is greater than or equal to 80% then, basing on the conducted tests, it is advised to:

1. Check if Graham's ratio is credible, i.e. if the value of its denominator is within the range of $0.2 < (0.265 \times N_2 - O_2) < 5.7$. If the value of the denominator is beyond the range, then at this stage of calculations, it is possible to discard the interpretation of fire hazard presented by this indicator. However, if Graham's ratio is within the credibility range, then it is necessary to move to point 2.
2. Check if the concentrations of gases meet the condition: ethylene $\leq$ 0.07 ppm, propylene $\leq$ 0.06 ppm, acetylene $\leq$ 0.007 ppm and carbon oxide $\leq$ 24 ppm. If the condition is met, then it may be assumed that the lowest level of fire hazard according to Graham's ratio is correct. Otherwise, it is recommended to apply other criteria to assess the level of endogenous fire hazard – e.g. the essential gases method (Trenczek, 2003).
3. It is worth mentioning that the more the concentrations of the aforementioned gases deviate from the given levels, the more it is certain that there is higher fire hazard than the values of Graham's ratio show it.

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