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CARBON DIOXIDE CONCENTRATION IN MINE WORKINGS

1. Introduction and aim of the paper

Carbon dioxide is a constituent of mine air. It flows along with atmospheric air into mine workings, in which its quantity may increase. In normal states of mine ventilation, where air expenditure flowing through the working has been quasi-established and no phenomena such as underground fires, explosions or violent gas effusions from the rock mass occur, the total contents of CO_2 in the air changes according to the range characteristic for the particular location in the mine. The shift of its concentration at some places within the mine also depends on the fluctuation of atmospheric pressure. This is related to the "barometric effect" in goaves, most distinct in mines where retreat mining is used. In spite of this variability of CO_2, the fluctuation range is characteristic for a given mine and owing to effective ventilation that works constantly, concentrations of that gas in mine air permissible by mining regulations are met.

Ore mines, on account of the nature of the deposit and its exploitation methods, are characterized by smaller mine-air fluctuations of CO_2 caused by geological-mining conditions. They are also dissimilar from coal mines with respect to the cause of this gas' increase in concentration within mine workings. Some of these differences are: mining with explosive materials and transport using combustion machines with diesel-fueled engines. Such machines are mobile sources of exhaust gases in mine workings, with carbon dioxide among them. The localization of these sources is related to the places of these machines' operation, but the increase in carbon dioxide concentration occurring in such places may also involve workings in the way of which air is removed to the surface. Regardless of this specificity, ore mines are also distinguished by a certain range of concentration variation of carbon dioxide in mine air.

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States in which the ranges of these variations are exceeded, signal unusual phenomena affecting the ventilation system or rarely occurring technical-organizational reasons (e.g. bad running condition of self-propelled machines, poor oil quality, or a work schedule in which the ventilation possibilities in the working area of self-propelled machines are not considered). It is essential that these signals are noticed and properly diagnosed by the ventilation service.

They could then undertake adequate endeavors to eliminate the causes of this state, or to diminish the danger these states pose to the mine crew.

The aim of this article is the description of such state, its preliminary analysis and formulating conclusions that might prove a useful tool for the ventilation service to effectively protect the crew from inadmissible CO_2 concentrations in the mine atmosphere.

2. The CO_2 concentration increase effect in the air within mine workings

The ventilation service passed the information that in a certain ore mine inexplicable increases of CO_2 concentration occur, exceeding the usual values in its workings. Following consultations, it turned out that the service had registered several events of strange reactions of people and machines at particular locations in the mine. People staying in certain places had typical symptoms of an increased carbon dioxide concentration (breathing difficulties, vertigo and headache), and machines had problems maintaining constant engine operation or issues with its restart.

Several times such states registered by the system were not necessarily related to the presence of a combustion machine in a given place. The ventilation service, after receiving information regarding this issue, performed measurements consisting in obtaining samples of mine air. Their results did not confirm the exceeding of gas concentrations in the mine atmosphere admissible by the mine regulations. Incidentally, however, the performed monitoring measurements of gas composition in that location indicated disturbances in air composition, sometimes exceeding the values admissible by safety regulations.

From then on, such states were registered by the ventilation service several times a year in two places apart from each other within the working ventilation system in the mine. Such manner of initial description of this state by the mine ventilation services, involving some dose of uncertainty, was justified.

The mine ventilation service were unable to provide a rational explanation of the causes of these states, or determine the area of their potential occurrences. It arises from their information, confirmed by single results of obtained air samples, that on occasion the concentration of oxygen in the atmospheric air lower than 19% had been registered in these places.

From the preliminary report of this phenomenon obtained from the mine service it appeared that we were dealing with an “intangible phenomenon” of unknown duration.

That alone posed a great challenge, since it was clear that the methodology and the manner of mine air measurement usually applied in the mine would not be very useful for the purpose of this research. Therefore other means of measuring the gas constituents of the mine atmosphere were sought. What proved helpful was the WIP-1 device, whose first copies had been produced and supplied for this research by the EMAG company in Katowice.

The WIP-1 device is designed for the simultaneous control of:

- the chemical composition of the atmosphere, including: the concentration of methane, oxygen, carbon monoxide, carbon dioxide and an extra gas from the group of SO_2, H_2S, H_2, NO, NO_2 chosen by the user;
- the physical parameters of air, such as: temperature, humidity, pressure, flow velocity.

The WIP-1 device may also be used for atmosphere control at any point of the working, including inaccessible places thanks to the application of the suitable telescopic extension arm WT-1/WIP-1. The measurement signal is then transmitted wirelessly to the readout panel PO-1/WIP-1. The analyzed air could also be obtained from inaccessible places with the use of the pump PA-1/WIP-1 and fed to the inlet of the sensors.

Besides the aforementioned components, a docking station of the UDS-1/WIP-1 type used for communication with a PC and battery charging is also included in the WIP-1 measurement set.

The WIP-1 device has extensive functions allowing for:

- simultaneous measurement of nine atmosphere parameters,
- visualization of the measured parameter values on the display,
- visualization of alarm and emergency states on the display,
- optical and acoustic signalization of alarm and emergency states,
- archiving measurement data,
- registering the time of performed measurements,
- wireless data transmission to the PO-1/WIP-1 readout panel,
- data transmission to the PC after finishing the measurement cycle.

At the same time it is an individual instrument that may be located in any given place. It works in a constant manner, in conditions determined by the manufacturer as follows:

- temperature range –20– –40°C,
- humidity range do 95% RH,
- pressure range 800–1200 hPa,
- supply voltage 12.0–14.5 V.

The circulation of the tested air is realized through diffusion, and power consumption amounts to 65 mA at the required voltage of 14 V.

With regard to its features, it should be mentioned that the measured values are registered in the internal EPROM memory including the time of the conducted measurement. The registered values can be transferred to the computer by means of data transmission via the RS 232 port.

The small weight of the device estimated at 800 g and its aforementioned features turned out to be very useful to tackle the posed problem.

The CO_2 measuring error in the range of 0÷2% amounted to ±0.1% CO_2, the O_2 measuring error was equal to ±0.6 %, and the CO error to ±3 ppm. The device's response time to the mentioned gases was lesser or equal to 20 seconds. The pressure measuring error in the 800÷1200 hPa range amounted to 0.2% of the indicated value, and the response time was lesser or equal to 30 seconds.

The air temperature measuring error was equal to ±0.5°C, and the response time was lesser or equal to 5 minutes.

Many (over 3000) measurements were conducted in two locations selected for that purpose: the workings and places in which the mine had earlier found accidental increases of CO_2 concentration, i.e. in exploratory heading 464 and heading 1000. The aim was not only to confirm the occurrence of atmosphere state incompliant with the regulations, but also to determine whether the temporal development of certain gas concentrations in the mine atmosphere bears any likeness to the technological cycle, for instance. The analysis of the obtained temporal courses of the examined concentrations did not indicate the mentioned similarity.

The CO_2 concentrations oscillated slightly around the value of 0.3%, which can be accepted as characteristic of the underground workings of the examined mine. Nor did the measurements confirm that the gas concentration values in the atmosphere exceeded those admissible by regulations. Statistical analysis, however, proved the existence of a significant linear correlation among the following measured parameters: CO_2, O_2, p, CO.

The second phase of testing conducted in those two places embraced a longer time horizon, in order to take into account the influence of larger pressure changes on the interrelated gas concentration values. The total number of measurements is 7151, lasting several months.

In the measurement period, the device registered a state in which the CO_2 and O_2 concentrations were inadmissible by mine regulations. The registered courses of the selected parameters [1], with the indicated time period of exceeding admissible values, are marked in the figures by the red line.

In Figures 1 and 2, illustrating the course of oxygen concentration changes, the dark blue points indicate the measured value, the light blue points indicate the systematic measurement error (amounting to ±0.6% in the case of oxygen).

As can be inferred from Figure 2, the state of oxygen concentration below admissible norms was successfully registered during the measurements in that particular working.

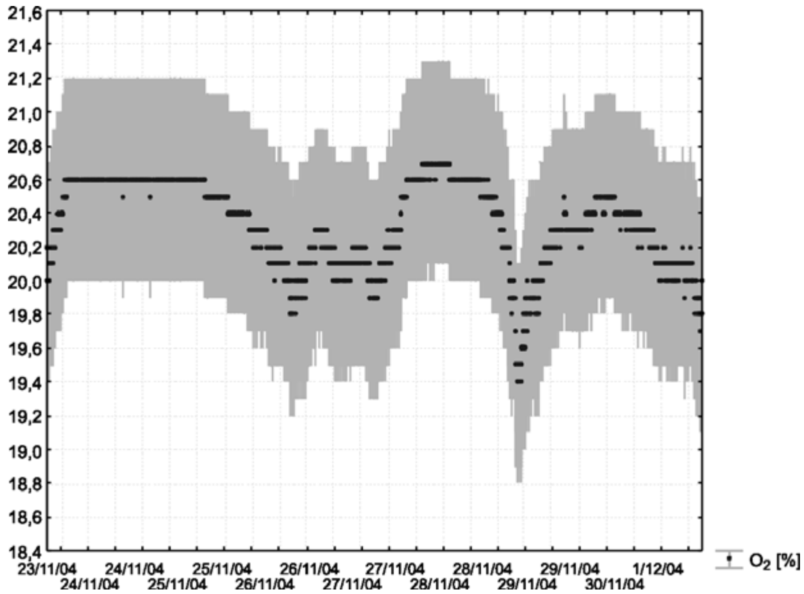

Fig. 1. The temporal course of oxygen concentration in the mine air established by the measurements in heading 464, with the indication of the systematic error range originating from the accuracy of the device [1]

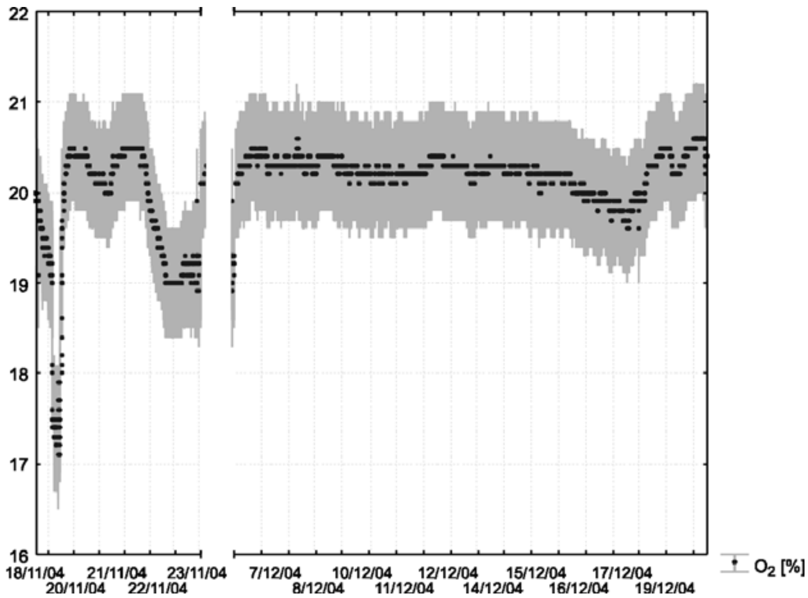

Fig. 2. The temporal course of oxygen concentration in mine air established by the measurements in exploratory heading 1000, with the indication of the systematic error range originating from the accuracy of the device [1]

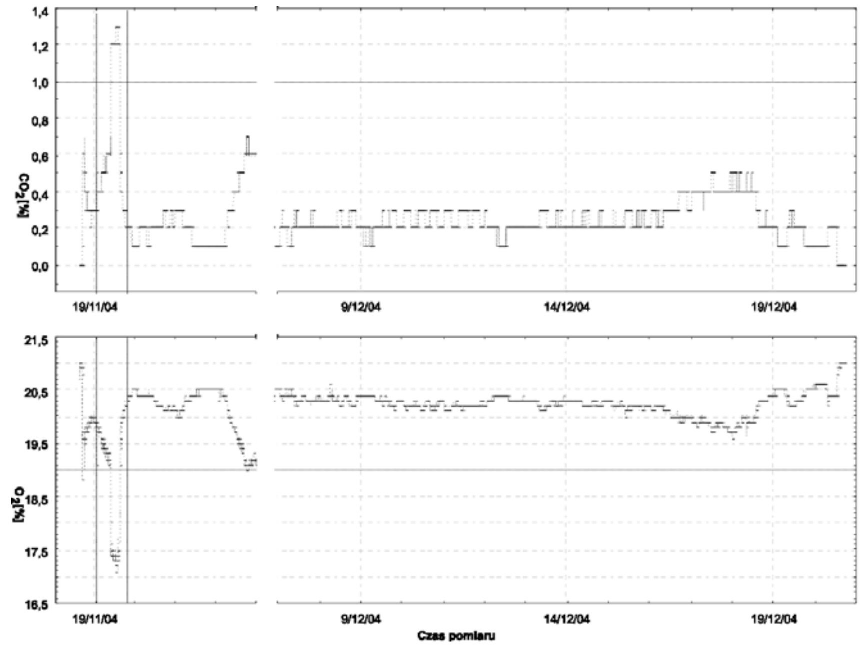

Fig. 3. The temporal courses of CO_2 and O_2 changes in the air of exploratory heading 1000

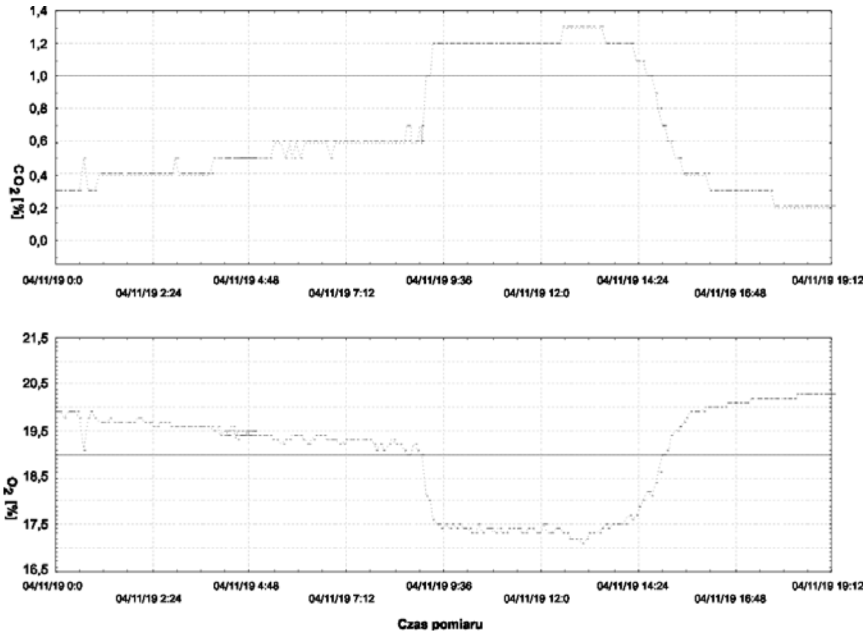

Fig. 4. Detailed temporal courses of CO_2 and O_2 in the air for the exploratory heading 1000 and for the black-bordered area in Figure 3

In order to portray the course of that phenomenon more clearly, fragments of interest have been magnified in graphs presenting the correlation of varying temporal courses. These magnifications were made only for heading 1000, as during the measurements the oxygen decrease below 19% had only been observed there.

The magnification of the graphical correlation of the courses shown in Figure 3 is presented in Figure 4.

From the courses presented in Figure 4 it is apparent that the state of exceeded admissible values of CO_2 and O_2, marked in the graph by the red line, lasted around 5 hours. The time period of such atmospheric state posed a health hazard for the crew staying in that location.

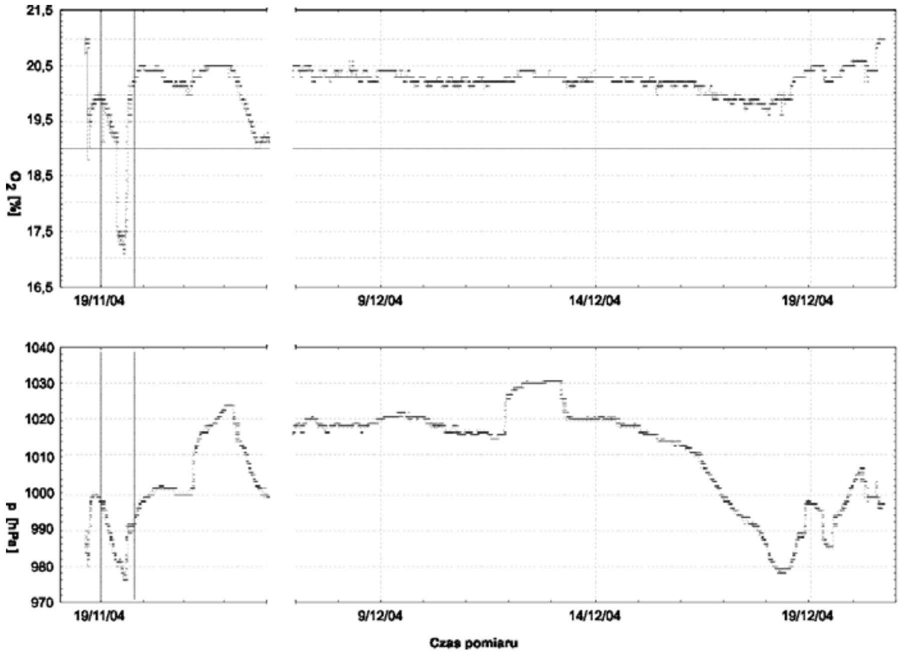

Fig. 5. The temporal courses of O_2 and air pressure changes in the exploratory heading 1000

In Figure 5 the courses of oxygen concentration and mine air pressure changes in the exploratory heading 1000 with the indication of the areas where air concentration exceeded the admissible level. This area is shown in detail in Figure 6.

The courses presented above confirmed the occurrence of the state where admissible concentration levels of oxygen and carbon dioxide in the exploratory heading 1000 were exceeded. Thus they verified the observations reported by the mine ventilation service, that such states had been found in heading 464 and the exploratory heading 1000. The conducted tests confirmed such states in exploratory heading 1000, but the registered concentration increase of CO_2 and the decrease of O_2 in heading 464 were close to admissible values. The courses of the tested parameters in exploratory heading 464 put together in pairs in Figure 7.

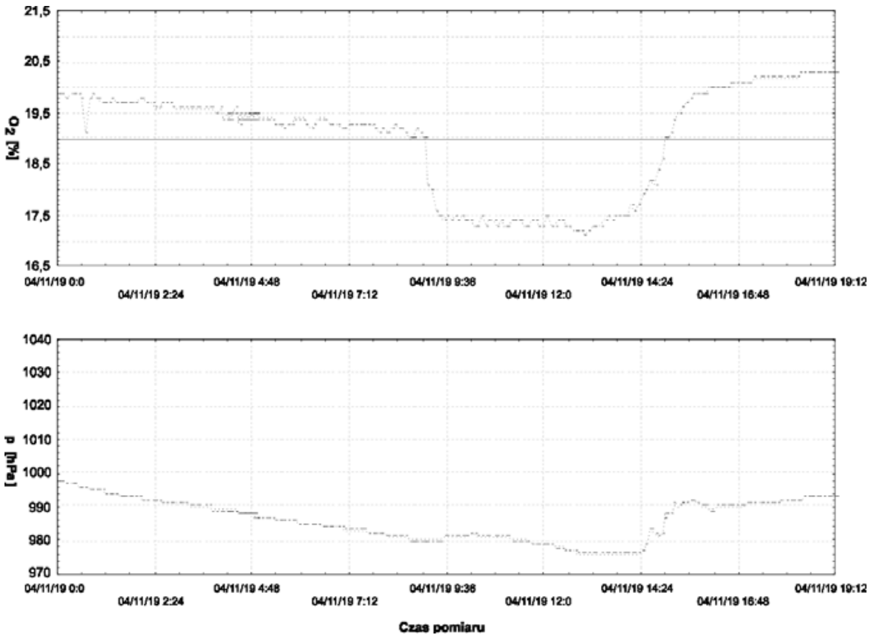

Fig. 6. Detailed temporal courses of O_2 and air pressure changes for the exploratory heading 1000 and the black-bordered area in Figure 5

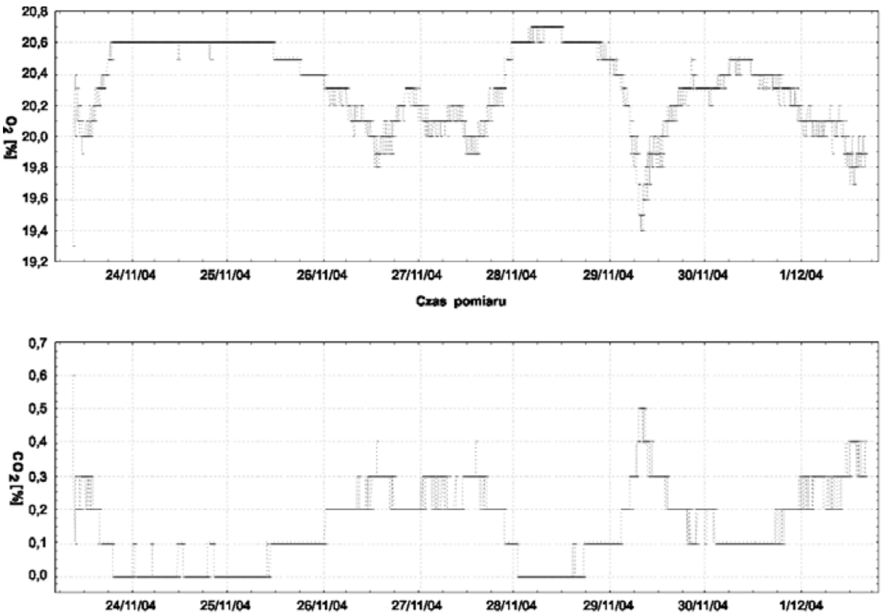

Fig. 7. Temporal courses of O_2 and CO_2 changes in mine air of heading 464

3. The analysis of correlation and multiple linear regression of the obtained measurement results

Some conclusions from the statistical analysis of the measurement results have been discussed in the paper [1].

Those that in the paper [1] were described superficially out of necessity, are focused upon below.

It has been mentioned that in the research a more reliable analysis of the correlation between the selected measured parameters was expected to be obtained. The higher reliability was based on the fact that the long research period provided the chance of registering the tested parameters in a broader range of their possible values.

Since the research cycle also involved the state of exceeding admissible values of CO_2 and O_2 concentration in the working, the reliability of linear interdependence between the examined parameters established on the basis of these results is even higher.

The research of the interdependence between these values is related to the correlation and regression problem. As four values were tested (p, O_2, CO_2, CO), then multiple linear correlation and multiple linear regression [2] is applicable to this case and the character of relation among the examined values.

Since the concentration of CO_2 in the air is our object of interest, in the research it will be a dependent variable whose value depends on the other three values, treated as independent variables.

We assume that the relation between these variables does not have a functional character connected with a known physical phenomenon, but a correlative one, additionally established in the preliminary tests as linear.

Marking the dependent variable with the symbol x_1, and the independent variables with the symbols: x_2, x_3, ..., x_k respectively, the solution of the usually complicated dependences linking the variables consists in carrying out the following computational-analytical stages [2].

In the field of correlation analysis:

— Determining the degree of linear relation between two variables, e.g. x_1 and x_2, while eliminating the influence of other variables, i.e. x_3, x_4, ..., x_k. This is achieved by calculating the so-called partial correlation factor, which is referred to as $r_{12.34...k}$. For comparison, the correlation factor r_{12} abbreviated to r, bears the name of simple correlation factor; its value may be altered by the uneliminated influences of other variables.

— Determining the degree of linear relation between the dependent variable, i.e. x_1, and all of the other variables x_2, x_3, ..., x_k. For this purpose, the so-called multiple correlation factor is calculated and marked by the symbol $R_{1.23...k}$. In the regression analysis, the regression plane equation is predicted by the formula

$$x_1 = a_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + \cdots + a_k \cdot x_k .$$

— Calculating the regression equations for two variables, e.g. x_1 and x_2, while eliminating the influence of other variables. In this case, the above equation is reduced to the form of

$$x_1 = a_1 + a_2 \cdot x_2 .$$

The factors $a_2 \cdot a_3 \cdots a_k$ are called directional factors of partial regression. They are often stated in the following way:

$$a_2 = a_{12.34-k} ,$$

$$a_3 = a_{13.24...k} ,$$

$$\dots\dots\dots\dots\dots$$

$$a_k = a_{1.234...k-1} .$$

The factor a_1 is called the shift factor of the regression equation and is specified in the following way

$$a_1 = a_{1.234...k} .$$

— Finding the multiple regression equation portraying the relation between the average value of the variable x_1 from all of the other variables. To put it in a different way, the task is to find the equation factor. Let us rewrite the equation applying the new symbols

$$x_1 = a_{1.23..k} + a_{12.34..k} \cdot x_k + a_{13.24-k} + \cdots + a_{1k.23-k-1} .$$

Taking into account the known analytical geometry formulas, the above equation can be stated in the following form

$$x_1 - \overline{x}_1 = a_{12.34-k} \left(x_2 - \overline{x}_2 \right) + a_{13.24..k} \left(x_3 - \overline{x}_3 \right) + \cdots + a_{1k.23-k-1} \left(x_k - \overline{x}_k \right).$$

Comparing both equations, we obtain the formula for the free term, which is the shift factor in this case

$$a_{1.23..k} = \overline{x}_1 - a_{12.34...k} \cdot \overline{x}_2 - \cdots - a_{1k.23..k-1} \cdot \overline{x}_k .$$

The multiple regression equation $x_1 = a_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + \cdots + a_k \cdot x_k$ is an equation of the “best plane” calculated with the least squares method and drawn through the measuring points.

The multiple correlation factor $R_{1.23}$ measures the quality of matching the points with the mentioned multiple regression plane.

The partial regression equations $x_1 = a_{1.23} + a_{12} \cdot x_2$, $x_1 = a_{1.23} + a_{13} \cdot x_3$ etc. are equations of the straight line drawn by intersecting the multiple regression plane with the planes 0 x_1 x_2 ; 0 x_1 x_3 , etc. respectively.

The partial correlation factors $r_{12.3}$, $r_{13.2}$ etc. measure the quality of matching of adequate point projections onto the partial regression lines.

The simple regression equations $x_1 = a_0 + a_{12} \cdot x_2$ etc. are derived from drawing the optimal line through the „marks" of the points projected orthogonally onto the planes $0\, x_1\, x_2$ etc.

The simple correlation factors r_{12}, r_{13} etc. measure the quality of matching the marks of measuring points with the simple regression line.

The correlation and regression analysis of numerous variables is a subtle tool for formulating measurement results, granting the possibility of isolating the influence of many different factors even in cases when such factors are impossible to isolate in practice [2].

Owing to the large size of the collected measurement data, it would be difficult to provide details of calculation on such data, therefore the Statistica software suite was used in calculation. Below only the final forms are presented in the manner of the multiple regression equation that describes the measurement results obtained in the two examined workings.

3.1. Evaluating the significance of the partial correlation and the multiple correlation factors

The significance of the partial correlation and the multiple correlation factors can be evaluated with the F-Snedecor test, among others, applying the proper formulas:

$$F = \frac{r^2_{ij.k...n}}{1 - r^2_{ij.k...n}}(n - k - 1), \qquad F_{\alpha, k_1, k_2} = F_{\alpha, 1, n-k-1},$$

$$F = \frac{R^2_{i.jk...n-k-1}}{1 - R^2_{i.jk...n-k}}, \qquad F_{\alpha, k_1, k_2} = F_{\alpha, k, n-k-1},$$

where:

n — number of measurements,

k — number of independent variables.

As usual in the case of the F-Snedecor test, if $F \le F_\alpha$, k_1, k_2 then the correlation is deemed insignificant, and if $F > F_\alpha$, k_1, k_2 then the correlation is deemed significant. Similarly to the earlier remark, it would be difficult to perform these calculations on such extensive data. Thus, the aforementioned Statistica suite was used.

Table 1 demonstrates the formulas used in the process of calculating the linear correlation and the multiple regression [2].

In consequence of applying the calculational algorithm of the Statistica suite based on the above formulas to the obtained measurement results, the following form of the multiple regression equation was obtained

$$CO_2\,[\%] = -0.000443 p\,[\text{hPa}] - 0.351774 O_2\,[\%] + 0.003964 CO\,[\text{ppm}] + 7.761743.$$

TABLE 1

Formulas for value calculation in the correlation analysis and the linear regression of many variables using the values applied in the simple linear regression and correlation analysis [2]

Number of variables	Partial correlation factors	Multiple correlation factors	The multiple regression equation and shift factors	Partial correlation factors, directional factors
k variables	$r_{12.34-k}=\frac{\left[r_{12.34(k-1)}-r_{1k.34..(k-1)}\cdot r_{2k.24-(k-1)}\right]}{\frac{\sqrt{\left(1-r^2_{1k.34..(k-1)}\right)}}{\left(1-r^2_{2k.34..(k-1)}\right)}}$	$R_{1.23..k}=\sqrt{1-\left(1-r^2_{12}\right)\left(1-r^2_{14.23}\right)...\left(1-r^2_{1k.23..(k-1)}\right)}$	$a_{1.23..k}=\bar{x}_1-a_{12.34..k}\cdot\bar{x}_2-\cdots-a_{1k.23-(k-1)}\cdot\bar{x}_k$	$a_{12.34..k}=r_{12.34-k}\frac{S_1}{S_2}$ $a_{1k.23-(k-1)}=r_{1k.23..k-1}\frac{S_1}{S_k}$
3 variables	$r_{12.3}=\frac{r_{12}-r_{13}\cdot r_{23}}{\sqrt{\left(1-r^2_{13}\right)\left(1-r^2_{23}\right)}}$ $r_{13.2}=\frac{r_{13}-r_{12}\cdot r_{23}}{\sqrt{\left(1-r^2_{12}\right)\left(1-r^2_{23}\right)}}$ $r_{23.1}=\frac{r_{23}-r_{13}\cdot r_{13}}{\sqrt{\left(1-r^2_{12}\right)\left(1-r^2_{13}\right)}}$	$R_{1.23}=\sqrt{1-\left(1-r^2_{12}\right)\left(1-r^2_{13.2}\right)}$	$x_1=a_{1.23}+a_{12.3}\cdot x_2+a_{13.2}\cdot x_3$ $a_{1.23}=\bar{x}_1-a_{12.3}\cdot\bar{x}_2-a_{13.2}\cdot\bar{x}_3$	$a_{12.3}=r_{12.3}\frac{S_1}{S_2}$ $a_{13.2}=r_{13.2}\frac{S_1}{S_3}$
4 variables	$r_{12.34}=\frac{r_{12.4}-r_{13.4}\cdot r_{23.4}}{\sqrt{\left(1-r^2_{13.4}\right)\left(1-r^2_{23.4}\right)}}$ $r_{13.24}=\frac{r_{13.4}-r_{12.4}\cdot r_{23.4}}{\sqrt{\left(1-r^2_{12.4}\right)\left(1-r^2_{23.4}\right)}}$ $r_{14.23}=\frac{r_{14.3}-r_{12.3}\cdot r_{24.3}}{\sqrt{\left(1-r^2_{12.3}\right)\left(1-r^2_{24.3}\right)}}$	$R_{1.234}=\sqrt{1-\left(1-r^2_{12}\right)\left(1-r^2_{13.2}\right)...\left(1-r^2_{14.23}\right)}$	$x_1=a_{1.234}+a_{12.34}\cdot x_2+a_{13.24}\cdot x_3+a_{14.24}\cdot x_4$ $a_{1.234}=\bar{x}_1-a_{12.34}\cdot\bar{x}_2-a_{13.24}\cdot\bar{x}_3-a_{14.23}\cdot\bar{x}_4$	$a_{12.34}=r_{12.34}\frac{S_1}{S_2}$ $a_{13.24}=r_{13.24}\frac{S_1}{S_3}$ $a_{14.23}=r_{14.23}\frac{S_1}{S_4}$

The quality of the determined multiple linear correlation is established by the so-called corrected correlation power, equal to 0.93938163. It indicates that nearly 94% of the measurement results are explained by the obtained correlative relation. The significance evaluation of the correlation factors also confirmed their significance.

4. Conclusions

1) On the basis of the measurements performed in an ore mine, it was found that the atmosphere state in one of the examined workings was inadmissible by the mining regulations. This state lasted around 5 hours, in spite of the efficiently-working ventilation.
2) 0In the period of the established increase, the CO_2 concentration in the air amounted to about 1.3% maximum and was accompanied by the decrease of the O_2 concentration in the air to the level of about 17%. In both cases the admissible value had been significantly exceeded.
3) In the experience of the ventilation service related to these events, there is no indication of the possibility of technical or organizational causes of such states registered in the past. Furthermore, no such causes were found in this research.
4) The particularly strong correlative relation between the concentrations of the examined gases and air pressure indicates the physical nature of the phenomenon causing these states. It is very probable that it is induced by a sufficiently severe decrease of air pressure. This would indicate the outflow of gas from the rock mass. It is in all likelihood carbon dioxide.
5) The obtained linear equation of multiple regression, matched so well with the results and in a broad range of values of the measured quantities, allows for its use in forecasting calculations.
6) For the conditions of the mine in which the above state had been found, it was determined that air pressure decrease to 950 hPa on the surface might induce the increase of carbon dioxide beyond admissible values. What remains is to locate the possible places of such increases. It results from the research that these could be the examined workings.
7) While being unaware of the exact causes of this phenomenon, but possessing the experience acquired through its research, it is probable that gas outflows from the rock mass may occur in a sufficiently fractured rock mass located in the vicinity of the boundary of the water run-off into a depression funnel. In order to confirm this, however, research into this field should be continued.

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