Review of applicability of using indicator gas coefficients for determining the temperature of the place of spontaneous combustion of coal

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Abstract. Spontaneous combustion of coal beds is considered to be one of the most hazardous effects of coal mining. The most dangerous factor of this process is its abruptness due to several types of coal possible emergence of reaction at low-temperature conditions and subtle reaction behavior at initial stage of the process, which may turn into environmental disaster. Therefore, on many mines and strip mines, in terms of occupation health and safety program and fire-preventing measures realization, fire monitoring system are introduced, as well as spontaneous combustion source monitoring system to apply fire-preventing measures. The most effective type of monitoring systems is gas monitoring, at which cause in many countries, including Russia, spontaneous combustion source indication methods based on fire gases concentration measurement are developed. Those methods are based on sharp increase of some specific gases, such as carbon monoxide and methane, at some point of spontaneous combustion source temperature, which differs depending on coal type and coal deposit. However, the application of those methods does not always allow the advance detection of coal spontaneous combustion areas, due to its low accuracy and dependence of fire-indication gases from external exposure. For that reason, many authors are advising ratios of fire gases or indicator gases ratios as a means of higher-precise spontaneous combustion sources indication method. In this paper, the analysis of those ratios applicability is conducted as well as existing underground fires indication methods.

1. Introduction

Coal is one of those types of minerals that have the property of spontaneous combustion in contact with oxygen in the air. Extinguishing or isolating the source in an open flame state is commonly used to control spontaneous combustion, which infrequently leads to the desired result. One of the effective measures to prevent endogenous fires is preventive methods, for example, monitoring gases emitted during the combustion of coal. One of the effective measures to prevent endogenous fires is preventive methods, for example, monitoring gases emitted during the combustion of coal. According to some sources [3, 13, 15, 16], coals of any type emit the following gases into the atmosphere at all stages of combustion: CO, CO\textsubscript{2}, H\textsubscript{2}S, CH\textsubscript{4}, H\textsubscript{2}, SO\textsubscript{2}, NO\textsubscript{2}. In addition to these gases, there were also cases of the release of radon [4], lower hydrocarbons C\textsubscript{1} – C\textsubscript{4} [16, 14], argon [5], and cases of the release of chloride and fluoride compounds from burnt dumps [6].

Gas monitoring of centers of spontaneous combustion is applied both in Russia and abroad. Similar gases are used as the main indicator gases in different ones: CO - In Russia, the USA, Germany, France
and Poland, joint analysis of CO and C2H4 - in Japan, England and China [16]. In addition to the main gases, in many countries, the analysis of the emission of specific gas emissions, which, when analyzing the kinetic parameters of coal and determining the temperature of the emission of these gases, can be used to develop preventive measures, has been used to predict changes in the source of spontaneous combustion.

However, it is often not possible to fix the release of specific indicator gases. In such cases, it is advisable to use indicator coefficients or the ratios of the concentrations of various basic gases to identify the early stage of coal spontaneous combustion.

2. Materials and methods

The main indicator coefficient used by many authors to identify the early stages of spontaneous combustion is the Graham coefficient, calculated by the formula [7]:

\[
GR = \frac{100(CO_f - CO_i)}{O_f - O_i}, \%
\]

where \(CO_i\) - is the final concentration of carbon monoxide,\%; \(CO_i\) - initial carbon monoxide concentration,\%; \(O_f\) - finished oxygen concentration,\%; \(O_i\) - initial oxygen concentration,\%.

According to the research [10, 11, 12], various values of the coefficient indicate the following condition of the focus:
- less than 0.4\% - Normal state;
- from 0.4 to 1\% - Unstable state;
- from 1\% - Heating;
- from 2\% - Open flame.

In addition to equation (1), other coefficient variations are often used, depending on local parameters. For example, when monitoring mines in real time, the following equation is more often used [11]:

\[
GR = \frac{100CO_f}{0.265N_f - O_f}, \%
\]

where 0.265 - is the ratio of oxygen to nitrogen concentration in atmospheric air, \(N_f\) - is the final nitrogen concentration,\%.

For the initial stage of the oxidation process, the authors of [2] proposed an analytical dependence:

\[
T = 456 \left(\frac{CO}{\Delta O_2}\right)^{0.0076}, K
\]

The authors of the work tested this approach at three enterprises: the «Pioneer» mine of Dobropolyeugol LLC, the mine n.a. Artyom GE “Luganskugol” and the mine “Komsomolets Donbass” PJSC DTEK. According to the results of experimental studies, the temperature of the combustion zones slightly differed from that obtained using the ratio of the concentrations of indicator gases characteristic of these mines (unsaturated hydrocarbons).

According to the research [11, 15], the Graham coefficient shows the most representative result with oxygen loss values of more than 0.3\%. In addition, the value of this ratio depends on the concentration of carbon monoxide, the increase or decrease in concentration of which, as the authors note [12], weakly correlated with a change in temperature and the source of fire behavior under certain conditions.

Similar to the Graham coefficient is the Young coefficient, where the indicator gas is carbon dioxide:

\[
YR = \frac{CO_2}{\Delta O_2}
\]

where \(CO_2\) - is the final concentration of carbon dioxide,\%.

The values obtained using the formula (4), which are less than 25 indicate the presence of heating, more than 50 indicate an open flame [12]. The Young coefficient has similar disadvantages: the most representative result is obtained with oxygen loss values of more than 0.3\%, the value of carbon dioxide concentration may differ from the true value due to adsorption in water. The coefficient is most often
used as an additional one to confirm the presence of spontaneous combustion processes, rather than as an independent indicator [13].

To analyze the status of underground fires, the Jones-Triquet coefficient is often used [5]:

\[ JT = \frac{CO_2 + 0.75CO - 0.25H_2}{\Delta O_2} \]  (5)

where \( H_2 \) - is the final concentration of hydrogen, %.

If there is a source of endogenous combustion of coal, the value of this coefficient will be in the range from 0.5 to 1.0. With a sharp decrease in the temperature of the focus or its attenuation, the value of the coefficient will not exceed 0.5 [12].

All of the above coefficients use the amount of oxygen loss as a measure of comparison, which is associated with the occurrence of such inaccuracies as the negative value of the coefficient, as described in the works [7, 11], and a non-indicative result for small values of oxygen loss.

To avoid inaccuracies associated with inconsistent levels of oxygen loss, the ratio of carbon monoxide to carbon dioxide is often used. This coefficient allows assessing the degree of combustion or the oxidation process, and by assessing the change in the coefficient with increasing temperature, you can determine the critical temperature of spontaneous combustion (CTSC). For example, in the study [8], the CTSC and crack temperature were estimated at four mines in China; as a result of the studies, graphs of the change in the ratio of gases with increasing temperature were obtained (Fig. 1).

![Figure 1. Changes in CO/CO₂ under rising temperatures](image)

An analysis of Figure 1 allows concluding that when the CTSC level and crack temperature are reached, the CO/CO₂ ratio increases sharply. Thus, even at the stage of preliminary studies of changes in the values of a given quantity for a particular field, it is possible to predict with high accuracy the state of the place of spontaneous combustion. However, as noted by the authors of the study [5], the determination by this method becomes possible at later stages of the development of processes preceding the combustion of coal, when the temperature of the center exceeds 200 °C. The authors of the study [12] give a more general value of this ratio for different conditions of the outbreak: for values less than 2 - there is burning in the adjacent territory, and for values of more than 13 - there is active burning.

A similar indicator characteristic is the ratio \( C2 / C1 \), where \( C2 \) is the concentration of ethane, \( C1 \) is methane. Peak values of the coefficient are manifested when certain processes occur in the coal, such as the attainment of CTSC, crack temperature and decomposition temperature (Fig. 2).
Figure 2 Changes in $C_2/C_1$ under rising temperatures

Using the coefficient data allow estimating the temperature of the area, which is in the range of from 50 to 300 °C [5].

There are also several rarely used gas ratios that are used in mines with certain conditions. For example, the authors of the study [9] proposed using the hydrocarbon coefficient to detect underground fires in depleted mines:

$$R_I = \frac{(1.01THC-CH_4)\times 1000}{THC-0.01}$$

where THC - is the total concentration of hydrocarbons, ppm; CH₄ - methane concentration, ppm.

When the coefficient values are from 0 to 50, the temperature in the outbreak is below the CCC, from 50 to 100 - a possible temperature increase in the studied area, and more than 100 indicates active heating of coal in the studied area.

This coefficient is not applicable to anthracites due to low hydrocarbon emissions, and also allows using only at a methane concentration of more than 20 ppm [9].

3. Discussion

In the course of the survey study, the practice of using indicator coefficients to predict the behavior of the center of spontaneous combustion and subsequent determination of the temperature of the center was analyzed. Thus, the Graham, Young, and Jones-Trickett coefficients are used in routine monitoring of the state of a self-ignition source, and it is advisable to analyze the joint change in the values of the coefficients to identify changes in the behavior of the source. The CO/CO₂ ratio is recommended to be used in the later stages of spontaneous combustion, when the temperature reaches 200°C or more, and the $C_2/C_1$ ratio in the initial stages when the temperature reaches 50°C. Some mines use special coefficients, like R1, which prove their effectiveness exclusively under strictly defined conditions of a limited number of fields.

The use of gas indicator coefficients has several advantages over the use of common indicators for predicting the state of a self-ignition source. For example, as it is shown in studies [8, 14, 16], a sharp change in the concentration of common indicator gases begins with a temperature mark of 75-80 °C, which does not allow timely application of the necessary safety measures in deposits of coal dangerous for spontaneous combustion, which this range.

The advantage of the above coefficients is also their low correlation to factors such as gas flow rate and a sudden change in flow direction, which makes it possible to significantly reduce the measurement uncertainty. However, the studies show that the development of a unified approach to assessing the
concentrations of unique indicator gases and the values of indicator coefficients for coals of specific deposits is relevant.

4. Conclusion
Main outcomes of the study are as following:

1. The use of indicator gas coefficients satisfies the conditions of the process of identifying spontaneous combustion and predicting the state of the source at each stage of the process, provided that the adopted model is adequate.

2. The assessment of changes in the center of spontaneous combustion by indicator coefficients is less sensitive to many external factors affecting the effectiveness of field research, compared with an estimate based on an analysis of the concentrations of common indicators, such as CO₂, CO, and others.

3. The joint use of the coefficients will improve the accuracy of the analysis of spontaneous combustion processes.

4. The analysis of the process for the release of special indicator gases to specific deposits (radon, hydrogen, chloride compounds) is characterized by a higher accuracy of the result than the analysis of indicator gas coefficients. However, this method is applicable only if there is information about the isolation of such compounds and preliminary kinetic studies to determine the temperature range over which it is possible to measure the concentration of such substances.

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