# IMPROVING SAFETY OF MINING OPERATIONS BY UPGRADING THE METHODS OF GAS PRESENCE MONITORING IN THE SHETH GROOVES

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ABSTRACT

The article deals with the areas and conditions of subterranean leakages initiation in caved areas for the main lava ventilation schemes. At present, all sheth ventilation schemes in coal pits, dangerous in what concerns gas explosion, can be differed over a number of known determining classification features in which the air leakage component is included. Aerodynamic sheth models are built. The list of factors determining the value and the direction of the leakages from the sheth grooves is given, and their origin is analyzed. The probable source of gas penetrating the sheth working zones is analyzed. The analysis of the conditions and causes of the accidents associated with gas and dust explosion that took place during the last twenty years has shown that their majority is constituted by those that took place at the sheths that develop low-angle formations with the development systems equipped with long pillars with complete weighing-down. Using the methods of statistic and technical analysis, we have uncovered that one of the main reasons for the disruption of normal gas conditions at the sheths is air leakage from the weighing-down area, as well as other gas sources located between the automated gas monitoring system gauges. Additional negative effect of the leaks is that their volumes constantly change in space and time at the development of gas-bearing formations using the systems characterized by significant volumes of the goafs. At present, the conditions of subterranean development at modern mining enterprises are often characterized by unsatisfactory forecast of the composition and quantity change characteristics of the mine atmosphere. This circumstance was the justification for the necessity to set the task of improving the methods of long-term and non-stop monitoring of these changes carried out using modern technical means and technologies in the automated mode. The task is to substantiate the necessity to develop and upgrade the methods of gas conditions control at the coal mine sheths basing on the estimations of the leakage dynamics from the weighing-down areas, and other gas emission sources. The main objective of the investigations is the development of practical measures to secure safety during mining operations in what concerns the gas factor.

# INTRODUCTION

The majority of Russian coal mines are gas-bearing formations; at that, the main volume of the deep mining in Russia is provided due to the application of the board-and-pillar methods with weighing-down (Ruban, *et al.*, 2011). Over 86% of coal mines are dangerous in terms of gas and coal dust explosion, over 50% of coal mines are classified as super-category

ones for methane and dangerous abrupt emissions (Paleev, *et al.*, 2011; Kolesnichenko, *et al.*, 2013). In such conditions, the issues of securing mining operations safety gain significant importance when explosion-hazardous gas accumulations are released to the atmosphere (Plotnikov, 1992; Petrosyan, 1998; Oganesyan, 2004; Ruban, *et al.*, 2011).

As the technical-and-economic indexes improve for

all mining processes, at the main production structurethe sheth, the lengths, cross-sections and the quantity of performed excavations, the sizes of the mine fields grow (Klishin, et al., 2011; Ruban, et al., 2011). Accordingly, the spaces of the goafs characterized by the presence of cavities in the caved areas grow as well. They serve as the air ducts, which hinders the ventilation management and, on the whole, affects the safety of the operations (Myasnikov, et al., 1987; Puchkov, 1993). The aerodynamic connection with the operating sheths of vast goafs, which are the highconcentration combustible gas collectors, enables gas penetration into the sheth working areas. When operations are performed on new sites, the caved areas of the exhaust mining fields continue to pose a significant danger from the point of view of the gas factor. Multiple explosions, blasts and inflammations of gas-air mixtures in collieries followed by fatalities were the result of these circumstances (Tarazanov, 2001-2014; Rosstat, 2013).

The caved area is a cavity filled with the mixture of various-size and various-shape fragments of caved debris. When rock breaks down, an environment penetrable for gas-air mixtures is formed (Miletich, 1962). The colliery air mixed with the released and formed gases fills all cracks and pores and represents a moving fluid, the motion of which is ruled by the main laws of aerogas dynamics in what concerns fractured porous media (Shashmurin, 1970). The caved area is the most difficult for the investigation and calculation part of the colliery ventilation networks where the role of the air leaks must be correctly accounted for to be able to efficiently manage the ventilation processes.

The peculiarity of the air leaks is that their amounts constantly change in space and time due to the advancement of the mining operations, performing new grooves and closing the old ones, installation of new and breaking the old ventilation facilities (Patrushev and Dranitsyn, 1974; Puchkov, 1993). This requires continuous control of the underground structures ventilation processes.

At present, solving the issue of improving the safety of operations is based on the implementation of the requirements stipulated in the "Safety Rules for Collieries" on the use of multi-purpose safety systems. The main subsystems in the conditions of gas and dust factors are the air-gas control systems (AGC) since the data received from them are used in many elements of the multi-purpose safety systems for the elaboration and implementation of required managing actions-technological and industrial measures, as well as used for informing the personnel

#### (GOST R, 55154-2012, 2012).

It has been discovered as a result of the investigation of the reasons of major accidents on collieries that in the majority of cases the monitoring of methane content in the sheth atmosphere during the period prior to the accident was within the design limits. However, one of the main reasons of explosions in collieries equipped with gas monitoring systems is the gassing in the uncontrollable zones of work areas. These facts suggest that very often in the conditions of collieries the automated gas monitoring systems are unable to secure absolute safety.

Thus, the topical issue is the development of scientifically substantiated methods of estimating the amount and composition of the air flowing in the sheth, including the caved areas, with parallel further improvement of the AGC systems. One of the directions of the improvement is the growth of the control instrumentation efficiency for a more comprehensive assessment of the gas release dynamics at the air motion in the sheth grooves. The main results of such measures aimed at the mining operations safety improvement in what concerns the gas factor are forecasting hazardous situations, early warning the operating personnel and undertaking measures for their protection.

# **TECHNIQUE**

#### Statistical investigations

The investigation technique was as follows.

- 1. The characteristic reasons of accidents in sheths, specified in the materials of technical investigations of the accidents followed by explosions, were determined.
- 2. All reasons causing the accidents were systematized basing on the main factors specific for the mining industry-natural, technical, organizational.
- 3. The reasons of the accidents associated with the sheth ventilation regime violation were shown in the form of diagrams. For the quantitative assessment of the leakage role in the accident associated with gas explosion, the statistical method was used to obtain the data on the distribution of frequencies and probabilities of accident occurrence for separate groups (clusters) in the colliery space and in time.

# **Field observations**

For the purpose of establishing the dependence of the leakage propagation, the experimental investigations of the weighing-down development systems in the

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colliery sheths with different ventilation schemesthrough-flow, reverse-flow and combined ones-were conducted. The observations were performed in a wide range of variations of air quantities flowing to a section to specify more accurately the character of the lava and adjacent sheths length-wise air distribution during one shift.

The on-site investigations in the production sections included the air-depression and gas survey under a standard technique, and individual air measurements at the places of probable air flow structure disruption (lava tailgates, boring machine operation areas, movable timbering sections). The aim of the measurements was to estimate the lava and adjacent sheths length-wise dynamics of direct and reverse flows into the goafs. The measurement of the mean air motion velocity was performed with the anemometer pass-by or point-wise method using a thermoanemometer in individual points of nearstope lava space transversal cross-sections; at that, their actual areas were determined.

The amount of air in lava and the corresponding values of leakages, as well as the width and the area of the ventilated area in the goafs were determined with calculation methods under known formulae.

The on-site investigations of gas emissions were performed to determine the locations of the combustible gas sources in the section, as well as their compositions and volumes. They included the gas-air survey of the section and individual determinations of combustible gas content at the points of their probable release and accumulation (caved areas, boring machine operation areas, nonventilated grooves, and goafs).

The observations at the gas survey included sampling the mine atmosphere with further analysis in the chemical laboratory and measurement of the mean air flow velocity at the places of sampling. Air samples were taken using the "wet method" with further analysis to be carried out using the chromatographic equipment. At that, methane, heavy hydrocarbons and hydrogen were identified.

### RESULTS

At the investigation of leakages as the reasons of emergency gas concentrations, a comprehensive detailed analysis was performed using statistical and technical methods (Smirniakov and Smirniakova, 2015). The performed statistical analysis of the gas emission reasons has shown that a large amount of emergency situations took place at the sheths in the proximity with the given locations of gauges (Fig. 1).



Fig. 1 Reasons and sources of gas release at faulty sheths.

The technical investigation has shown that the main organizational reason of gas concentrations is associated with the absence of up-to-date gas conditions monitoring at the sheth (Fig. 2).

At the analysis of technological diagrams of the weighing-down sheths in the collieries of coal producers, the main lava ventilation schemes shown in Figs. 3 and 4 were studied. For illustration purposes, Fig. 3 and 4 also show the calculated aerodynamic models of the sections with the pressure profiles.

Leakages at the reverse-flow ventilation design at the direct and retreat excavation order are principally different by the size and the structure of the goaf entrances (Smirniakov and Smirniakova, 2016).

At the direct excavation, with the motion along the lava mine tunnel, the main portion of air leakages into the goaf was discovered at the section 2-3-4-5, and is determined by the pressure difference  $\Delta P_{\scriptscriptstyle 2,3}$  $\Delta P_{4.5}$ . This section is determined by the aerodynamic resistance of the zone of unestablished support pressure formed behind the lava, and can exceed the main roof weighing-down step. Isolators on the mine tunnels and goaf interfaces also have significant resistance. Such design is distinguished by the relatively even air distribution in lava and, hence, even distribution of leakages in the goaf. Its main drawback is that relatively small amounts of air flow into the lava. The minimum depression causing the leakages is close to the lava depression,  $\Delta P_{3.4'}$  the maximum depression is determined as  $\Delta P_{2-5}$  (Fig. 3a).

At the retreat excavation, the major air leakage into the goaf at the section 2-3-4-5 is marked at the mine tunnel junction with lava to the goaf, as well as along its length, and can be determined by the corresponding pressure difference,  $\Delta P_{2.5}$ . This section is determined by the zone of unestablished support pressure formed behind the lava, and usually corresponds to the main roof weighing-down step. The value of leakages significantly depends on the aerodynamic resistance of the lava junction with the mine tunnel, timbering section resistance, boring machine position in the lava, and the condition of the direct weighed down roof. With such design, the mount and dynamics of leakages, as well as the aerogas dynamic environment in the lava, are mostly affected by the dynamic main roof caving both at the weighing-down moment, and during the following period. The determination of the leakage area boundary character in the goaf is difficult due to the lack of places where measurements can be



Fig. 2 Organizational reasons of gas concentration at faulty sheths.

performed, as they can be made in lava only. The maximum depression causing the leakages is close to the lava depression, h2-5; the minimum depression is determined as  $\Delta P_{3.4}$  (Fig. 3b).

Leakages at the direct-flow ventilation design at direct and retreat excavation differ mainly by their directions immediately in lava.

At the direct excavation, with the motion along the lava mine tunnel, the main portion of air leakages into the goaf was discovered at the section 1-2-4-5, and was determined by the pressure difference  $\Delta P_1$  $_{2}$ - $\Delta P_{4-5}$ . This section is asymmetrical; it has isolators with aerodynamic resistance, unsettled support pressure area resistance formed behind the lava, resistance of unsupported sheth 4-5, resistance of the timbering sections, and conditions of weigheddown immediate roof, and can exceed the main roof weighing-down step. Such design is characterized by the most uneven leakage distribution. The main disadvantage here is that uneven length-wise air penetration into lava is discovered. The minimum depression causing the leakages is close to the lava depression,  $\Delta P_{2.5}$ ; the maximum depression is determined as  $\Delta P_{1-5}$  (Fig. 4a).

At the retreat excavation, the major air leakage into the goaf at the section 2-3-4-5 is marked at the mine tunnel junction with lava to the goaf, as well as along its length, and can be determined by the corresponding pressure difference,  $\Delta P_{2,3}$ - $\Delta P_{4,5}$ .



Fig. 3 Reverse-flow ventilation designs and aerodynamic models of sections: a) at the direct excavation; b) at the retreat excavation.

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Fig. 4 Direct-flow ventilation designs and aerodynamic models of sections: a) at the direct excavation; b) at the retreat excavation.

This section is also distinguished by the area of unsettled support pressure behind the lava; it has asymmetrical character and can significantly exceed the main roof weighing-down step. The value of leakages significantly depends on the aerodynamic resistance of the lava junction with the mine tunnel, timbering section resistance, boring machine position in the lava, and the condition of the direct weighed down roof. The main drawback here is that uneven air withdrawal is discovered along the lava length able to cause the emergence of dead-air regions and, as a consequence, emergence of local methane accumulations. With such design, the mount and dynamics of leakages, as well as the aerogas dynamic environment in the lava, are affected by the dynamic main roof caving both at the weighing-down moment, and during the following period. It is hard to determine the character of the leakage area boundaries in the goaf due to large number of factors affecting the leakage dynamics. The minimum depression causing the leakages is close to the lava depression, h2-5; the maximum depression is determined as  $\Delta P_{2-4}$  (Fig. 4b).

The main locations of potential gas release points in the comparison with the locations of gauges within the sheths for various ventilation designs are shown in Fig. 5.

Extra points for gauges in all potential areas of active methane-air mixture formation and points of probable formation of layered methane accumulations are not clearly specified in the design documentation, as their locations depend on many factors and are determined on-site during the mining activity. As Fig. 5 suggests, the installation of stationary gauges is not envisioned in many points of potential gas release.

The analysis of the above-stated data helps to give prominence to a number of drawbacks of the existing AGC systems as follows:

- limited number of atmosphere monitoring points due to the static gauge positions, which does not allow analysis of the leakage effect on the section gas environment;
- insufficient response time of the system in emergency situations due to split arrangement of gauges;
- it is impossible to reliably determine layered and local accumulations, as well as in the case of uneven Smethane concentration distribution;
- inefficient operation in case of emergency situations.

The authors consider that the specified drawbacks are, mainly, due to the requirements to the organization and architectural principles of the AGC complex that do not allow on-site alterations of locations and connection of extra gauges.

## DISCUSSION

During the observations, we have discovered that the



Fig. 5 Locations of AGC gauges in the sheths and probable gas release point.

main factors that determine the values and directions (paths) of the leakages on the corresponding branch are as follows: depression of the branch; aerodynamic resistance of the branch; aerodynamic resistance of the entrances to the roof weighing-down areas, and convergence of the leakages with the main air flow.

The leakage flow lines shown in Fig. 3 and 4 are considered for the conditions of flat flow, when the altitude coordinate for all points of the chosen space are within the limits of the excavated rock of the formation, and can be deemed negligible. In practice, the intensely ventilated goaf area has the heights comparable with its length and width. The leakage flow lines in the 3D coordinate system, depending on the change of the pressure differences in the goaf node points, have complicated configuration; however, in the first approach their boundary can correspond to the formed dome of rock weighing down behind the lava.

The notion "unsatisfactory monitoring" as the main organizational reason for gas concentrations is associated with the absence of the timely monitoring of gas environment. At the air flow rate and gas concentrations measurements at the goaf, this reason also has a technical constituent. At the stationary methane release, an assumption is made that each unit area of the coal formation releases one and the same volumes of methane. In such case, the methane concentration as it flows through the goaf grows with the incremental total. But there are a number of processes followed by extreme gas releases into cleaning and preparatory goafs, when within a short period of time the amount of methane, very quickly forming the explosion hazardous concentrations, is released from quite a small area of the coal formation or from another point source. Even a regular connection element in the air room is able to let through itself different amounts of methaneair mixture depending on the pressure difference (air room depression). In the presence of several air rooms with different technological designs, their effect is able to significantly and within a short period of time change the concentration of the flow entering the lava, and the fixation of such event can

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only be carried out by the gauge located in front of the lava (Fig. 5).

The difficulty of protection in such situation is the presence of transport delay, determined by the velocity of the moving air and sheth length. According to the Safety Rules, the allowable air motion velocity in the cleaning grooves is 0.5 m/s to 4 m/s, in the preparatory ones-0.15 m/s to 6 m/s. The length of the cleaning stope is up to 300 m, preparatory grooves-up to 2000 m; the transportation constituent of the delay may equal up to several thousand seconds.

The investigation results for the air composition performed as gas-air surveys suggest that the gas environment in the groove atmosphere, which quantitatively can be assessed by the level of concentrations in the working area, depends on the ratio of the total amount of gas release to the amount of air supplied to the groove. At that, in the groove space, the convective-diffusion methane transportation is carried out, which in the general form can be represented in the form of a mathematical model describing the dynamics of the methane concentration change along the groove. The total gas release in the grooves can be represented as the sum of the gas emissions from various sources with the time-wise varying intensity.

Gas release from the near-slope area and from the groove surface can be represented as the sum of methane released from the surface of exposed coal formation with intensity varying in time. Gas emission from loosened coal, apart from the intensity varying in time, is characterized by the source location shift within the groove space at its transportation. Gas release from point sources usually takes place in the form of bleeding from large cavities and cracks; it can be associated with the areas of tectonic disturbances or can be localized near the air rooms with goafs. Gas releases from a goaf, both distributed along the goaf lengths and localized through the air rooms, depend on the dynamics of the leakages and air inflow from the caved areas.

The share in the total balance determined by this or that source depends both on the source intensity at the present moment and the period of time after the start of the gas release process. At that, the share of the sources in the gas balance can be determined more correctly only over the results of field observations. The conducted investigations suggest the conclusion that the total gas release in the preparatory grooves can be represented as the summarized value of separate gas releases from various sources with different periods of activity. The effects that change the intensities of the gas release sources can be both external technological operations associated with excavation and internal mining and geological factors.

We propose installation of extra gauges at lengthy excavation areas with potential points of gas release to improve the AGC system response.

By taking the initial concentration at the point of an AGC system gauge location (e.g., at that entering the section) and determining the concentration according to safety rules, we can determine the distance at which such concentration can be reached. Installation of the next AGC gauge can be recommended at such a place.

This solution will help reduce the time of transportation delay in case of intense gas releases. Since the air velocity in the groove is a variable, to determine the value of the delay, we need to adopt the corresponding air velocity in the groove out of the range of its variation. If we adopt the required value of the transportation delay for a certain distance, then the required amount of methane detecting gauges in the groove is determined as the groove length/given distance ratio.

#### CONCLUSION

The results of the comprehensive statistical and technical analysis of the interaction of the given data on the reasons and sources of the gas emission in grooves causing explosions suggest the conclusion about a significant effect of leakages into the chosen rooms on the atmosphere composition in the cleaning and preparatory grooves and its alteration dynamics.

Since the main operation safety requirements in terms of the gas factor are basically aimed at securing the efficient ventilation of the excavation areas, the timely determination of the leakage character contributes to the reliable assessment of the aerological environment in the cleaning grooves and is one of the major measures for its monitoring.

Basing on the analysis of the above described, we have discovered that the most significant feature of all stationary AGC systems is a long time of gas-air mixture travel within the preparatory and cleaning grooves between the gauges (in lava between the boring machine gauge and the gauge located on the lava outlet, in the preparatory groove between the gauges at the extraction column beginning and the gauge in front of the lava), which significantly reduces the AGC system operation efficiency in terms of the timely response to the growth of concentration. Thus, the main drawback that affects the efficiency of the existing automated gas monitoring systems at modern excavation areas in collieries is the delay period determined by the air flow velocity and the groove length. In some preparatory grooves, the delay time can equal up to several thousand seconds which is intolerable in certain situations.

The substantiation of the points of the installation of extra stationary gauges at lengthy sections of grooves with potential points of gas release to improve the AGC response is the solution that will help shorten the transportation delay in case of intense gas releases. The amount of extra gauges determined depending on the transportation delay and the groove length can be determined basing on the current air-gas environment in the groove.

The installation of extra gauges at lengthy sections of grooves with the points of potential gas release is the measure aimed at improving the safety of mining operations in what concerns the gas factor.

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