Features of the Working Area Aerogasdynamics with the Direct-flow Ventilation Scheme
Spatayev N.D., Sattarova G.S., Nurgaliyeva A.D., Balabas L. Kh.

Karaganda technical university, Department of «Mine aerology and a labor safety»
100027, The Republic of Kazakhstan, Karaganda, Ave. Nursultan Nazarbayev, 56

Abstract
To control rock pressure in the Karaganda coal basin, various technological schemes are used for mining and developing coal seams. At the same time, in order to form healthy and safe working conditions at workplaces in coal mines in the course of mining operations, it is necessary to ensure effective ventilation of the development and breakage faces.

When solving the problem of aeration of stopes, the authors of the article propose to take into account air leaks through the collapsed coal-rock mass of the goaf when controlling gas emission of an working area. For this purpose, the gas-dynamic state of the goaf has been studied under various conditions of ventilation: when isolating the longwall face goaf, when demolishing the supported ventilation working, when the amount of air supplied to the longwall face is changed and for refreshing, as well as a combination of these options. Experimental studies have been carried out in the mines of the Karaganda coal basin. This article took into account the features of the working area aerogasdynamics with the direct-flow ventilation scheme. As a result of the study, a quasi-network model of the working area and an algorithm of calculating air leaks through the collapsed goaf massif have been developed.

Keywords: quasi-network model, goaf, air leaks, depression residuals, direct-flow ventilation scheme

1 Introduction
In coal mines, the most hazardous methane emissions are working areas. The presence of the complicated air-gas situation in these areas can lead to an explosion of the methane-air mixture with the most serious consequences. The determining factor in the ventilation of the working area is the amount of air supplied to the longwall face and its leakage through the rock massif caving zone. Due to air leaks, a significant part of methane is removed from the longwall face directly into the ventilation working. At the same time, this leads to decreasing the amount of air participating in the ventilation of the face space of the longwall, and gas pollution of the interface with the ventilation tunnel. Therefore, in order to prevent gas pollution of stoping and supported ventilation workings with the direct-flow ventilation scheme, it is necessary to take into account and to control air leaks through the worked-out space (Akimbekov A.K. et al.1997).

It is not possible to measure directly the aerodynamic parameters of the goaf in mine conditions. This circumstance complicates solving the ventilation problem. Therefore, to simplify solving the problem, the entire permeable zone of the collapsed goaf is replaced by a quasi-network model. The structure of the model is as close as possible to the real rock massif. On the basis of this model, theoretical and experimental studies were carried out to determine air leaks from the longwall face and its inflows into the supported ventilation working.

The purpose of this article is to present a quasi-network model of the stoping area and an algorithm of calculating air leaks through the collapsed goaf massif. The calculation algorithm permits mine managers to provide optimal ventilation parameters for the working area and to ensure the use of the most effective aerodynamic methods of combating gas in coal mines.

2 Background
The Karaganda coal basin is one of the largest coal basins in the world located in Central Kazakhstan. The mines of the Karaganda coal basin are distinguished by a high gas content of the developed coal seams, which poses a real threat to the life and health of miners. The mines are classified as supercategorized for methane gas therefore, when organizing ventilation all the established industrial safety requirements must be strictly observed.

In the mines of the Karaganda coal basin, alongside with the return-flow ventilation scheme, the direct-flow scheme is also used. When developing coal seams with the direct-flow ventilation scheme, mined spaces of a significant area and volume are formed, which have a significant impact on the ventilation mode of working areas. The experience of using this technology in the conditions of the Karaganda coal basin has shown its rather high efficiency. It allows significant increasing the load on the breakage faces, reducing the volume of development workings, eliminating the loss of coal in the pillars, and providing safe working conditions for miners (Kaliyev S.G. et al.1987; Drizhd I.N. et al.1991).
3 Quasi-network model of the goaf

Figure 1 shows the direct-flow ventilation scheme for the working area. The stope (3-4) is a diagonal element, that is, it is located in the potentially unstable ventilation zone. The specified direction of the air flows movement and air leaks through the goaf, according to the properties of the diagonal joints, is ensured when the following condition is met:

\[
\frac{R_{1,2} + R_{2,3}}{R_{1,4}} < \frac{R_{3,5}}{R_{4,5}}
\]  

(1)

where

- \( R_{1,2}, R_{1,4}, R_{2,3} \) are aerodynamic resistance of the workings that delineate the mining section, daPa s\(^2\)/m\(^6\);
- \( R_{3,5} \) is aerodynamic resistance of the goaf, daPa s\(^2\)/m\(^6\);
- \( R_{4,5} \) is aerodynamic resistance of the supported ventilation working, daPa s\(^2\)/m\(^6\).

Aerodynamic parameters included in expression (1) are not stable. They change in the course of moving the breakage face. This can lead to the equality of these relations or changing the sign of the inequality. The indicated changes in the vector of leaks can lead to the overturning of the air flow movement in the zone where the longwall face meets the ventilation working.

To study the effect of aerodynamic characteristics of the collapsed rock massif and active workings on the nature of the gas-air flows distribution, it is proposed to use the quasi-network model of the worked-out longwall space (Levitsky Zh.G. 2013) shown in Figure 2.

Under the conditions of the current stope, the point located in the area of conjugation of the breakage face line and the wall of the supported working from the side of the worked-out space is taken as the origin of coordinates. The OX axis is directed along the wall of the supported stope. The OY axis is directed along the line of the breakage face, the OZ axis is directed perpendicular to the bedding plane. The number of branches connecting the nodes in the longwall face and ventilation workings and simulating the directions of air movement through the collapsed space varies from 1 to \( n \) depending on the size of the goaf. Thus, this model represents a complex ventilation scheme with 3\( n \) branches, 2\( n + 1 \) nodes and \( n \) independent contours.
Assuming that the pressure losses through the goaf obey the linear law, the system of equations describing the studied scheme for a given direction of bypassing the contours has the form:

\[
\begin{align*}
\sum_{i=1}^{n} R_{r,i} Q_{r,i}^2 + \sum_{i=1}^{n} R_{x,i} Q_{x,i}^2 - r_{i}q_{i} &= 0; \\
\sum_{i=1}^{n} R_{r,i} Q_{r,i}^2 + \sum_{i=1}^{n} R_{x,i} Q_{x,i}^2 - r_{i}q_{2} &= 0; \\
\sum_{i=1}^{n} R_{r,i} Q_{r,i}^2 + \sum_{i=1}^{n} R_{x,i} Q_{x,i}^2 - r_{i}q_{3} &= 0; \\
&\vdots \\
\sum_{i=1}^{n} R_{r,i} Q_{r,i}^2 + \sum_{i=1}^{n} R_{x,i} Q_{x,i}^2 - r_{n}q_{n} &= 0,
\end{align*}
\]

(2)

where

- \( Q_{r,i} \) : is the air flow rate in the \( i \)-th section of the stope, \( \text{m}^3/\text{s} \);
- \( Q_{x,i} \) : is the air flow rate in the \( i \)-th section of the supported ventilation working, \( \text{m}^3/\text{s} \);
- \( q_{i} \) : is the air leaks in the \( i \)-th direction through the collapsed massif, \( \text{m}^3/\text{s} \);
- \( R_{r,i} \) : is aerodynamic resistance of the \( i \)-th section of the stopping ventilation working, \( \text{daP} \cdot \text{s}^2/\text{m}^6 \);
- \( R_{x,i} \) : is aerodynamic resistance of the \( i \)-th section of the supported ventilation working, \( \text{daP} \cdot \text{s}^2/\text{m}^6 \);
- \( r_{i} \) : is aerodynamic resistance of the \( i \)-th direction through the collapsed massif, \( \text{daP} \cdot \text{s}/\text{m}^3 \).

4 Determining air leaks through the goaf

If we take the air leakage through the goaf \( q_{i}, \; i = 1, n \) as independent flow rates, then the amount of air entering the corresponding section of the design scheme will be determined as follows:

- for the longwall face:
  \[
  Q_{r,i} = Q_{r} - q_{i};
  \]
  \[
  Q_{r,2} = Q_{r} - (q_{1} + q_{2});
  \]
  \[
  Q_{r,3} = Q_{r} - (q_{1} + q_{2} + q_{3});
  \]
  \[
  \vdots 
  \]
  \[
  Q_{r,i} = Q_{r} - \sum_{j=1}^{i-1} q_{j}, \; i = 1, n ;
  \]
  \[
  \quad (3)
  \]

- for the supported ventilation working:
  \[
  Q_{x,1} = (Q_{x} + Q_{x}) - q_{1};
  \]
  \[
  Q_{x,2} = (Q_{x} + Q_{x}) - (q_{1} + q_{2});
  \]
  \[
  Q_{x,3} = (Q_{x} + Q_{x}) - (q_{1} + q_{2} + q_{3});
  \]
  \[
  \vdots 
  \]
  \[
  Q_{x,i} = (Q_{x} + Q_{x}) - \sum_{j=1}^{i-1} q_{j}, \; i = 1, n ,
  \]
  \[
  \quad (4)
  \]

where

- \( Q_{x} \) : is the air amount supplied for the longwall face ventilation, \( \text{m}^3/\text{s} \);
- \( Q_{n} \) : is the air amount supplied for refreshing the outgoing jet, \( \text{m}^3/\text{s} \).

Having substituted (3) and (4) into expression (2), we will obtain a closed system of equations relative to the unknown independent air flow rates \( q_{i}, \; i = 1, n \), that satisfies the first and second laws of ventilation networks (Tsoi S. and Rogov E.I. 1965; Levitsky Zh.G. and Nurgaliyeva A.D. 2018):
\[
\sum_{i=1}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right)^2 + \sum_{i=1}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right)^2 - r_i q_i = 0; \\
\sum_{i=2}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right)^2 + \sum_{i=2}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right)^2 - r_i q_i = 0; \\
\sum_{i=3}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right)^2 + \sum_{i=3}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right)^2 - r_i q_i = 0; \\
\vdots \\
\sum_{i=n}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right)^2 + \sum_{i=n}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right)^2 - r_i q_i = 0.
\]

(5)

This system of equations is nonlinear and is solved by the Newton linearization method. The essence of this method consists in the linear approximation of the nonlinear laws of networks. As a result of solving equation (5), the calculated values of the air flow rate for each section of the longwall face are determined. However, they do not always correspond to the actual data. This is due to the fact that with the direct-flow ventilation scheme, the air flow rate varies along the length of the mine. At the same time, air leaks through the goaf have affect significantly the degree of the air movement turbulence, as well as such parameters as the Reynolds number and the coefficient of aerodynamic resistance. Therefore, the calculated air flow rates need to be adjusted for air leaks through the goaf.

5 Calculation of the depression residuals and air flow rate corrections

To calculate depression residuals there are given approximate values of air leaks \( q_i^*, i = 1, n \) under the condition \( Q_d \geq q_1^* + q_2^* + q_3^* + \cdots + q_n^* \). Having substituting them into equation (5) there are determined depression residuals \( \Delta h_i, i = 1, n \) for all the contours of the quasi-network model.

A linear system of equations for calculating corrections \( \Delta q_i, i = 1, n \) to the accepted approximate values of air leaks \( q_i^*, i = 1, n \) is formed on the basis of equation (5) according to calculations provided in the book «Analyzing and controlling ventilation networks» (Levitsky Zh.G. and Nurgaliyeva A.D. 2018). After some transformations and collecting terms, we will obtain a linear system of equations in the form:

\[
\begin{align*}
(C_1 + 0.5r_1)\Delta q_1 + C_2\Delta q_2 + C_3\Delta q_3 + \cdots + C_n\Delta q_n &= 0.5\Delta h_1; \\
C_1\Delta q_1 + (C_1 + 0.5r_2)\Delta q_2 + C_3\Delta q_3 + \cdots + C_n\Delta q_n &= 0.5\Delta h_2; \\
C_1\Delta q_1 + C_2\Delta q_2 + (C_3 + 0.5r_3)\Delta q_3 + \cdots + C_n\Delta q_n &= 0.5\Delta h_3; \\
\vdots \end{align*}
\]

(6)

where \( \Delta h_1, \Delta h_2, \Delta h_3, \ldots, \Delta h_n \) are depression residuals for corresponding contours of the design scheme, daPa.

The \( C_{i}, i = 1, n \) coefficients in the system of equations (6) are calculated in accordance with the dependences:

\[
C_1 = \sum_{i=1}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right) + \sum_{i=1}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right), \\
C_2 = \sum_{i=2}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right) + \sum_{i=2}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right), \\
C_3 = \sum_{i=3}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right) + \sum_{i=3}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right), \\
\vdots \\
C_n = \sum_{i=n}^{n} R_{i,j} \left( Q_i - \sum_{j=1}^{n} q_j \right) + \sum_{i=n}^{n} R_{i} \left( \sum_{j=1}^{n} q_j - \sum_{j=1}^{n} \right).
\]

(7)
Solving system (6), we obtain the required corrections $\Delta q_i$, $i = 1, n$. Taking into account the determined corrections, the values of air leaks $q_i^*, i = 1, n$ are corrected according to the formula:

$$q_i = q_i^* + \Delta q_i , i = 1, n$$  (8)

6 Algorithm of determining air leaks

The above procedure of solving the problem of calculating air leaks $q_i$, $i = 1, n$ is reduced to the algorithm shown in Figure 3.

Below there is a description of this algorithm.

Step 1: Determining the actual values of air flow rates.

Step 2: Setting the initial values $q_i$ for air leaks.

Step 3: Checking the condition $\sum q_i \leq Q_0$. If this condition is not met, it is necessary to revise the correctness of specifying the initial data.

Step 4: Specifying the distribution of air flow rates in the calculated model scheme, aerodynamic resistances of all the branches of the design scheme.

Step 5: Mathematical describing the quasi-network model based on the first and second laws of ventilation networks in accordance with equation (5).

Step 6: Calculating depression residuals $\Delta h_i$, $i = 1, n$ for all the independent contours of the design scheme.

Step 7: Estimating the found $\Delta h_i$ with the given calculation accuracy.

Step 8: Forming a system of equations (6) to calculate the corrections $\Delta q_i$ for the assumed air flow rates. New air flow rates for all the branches of the design scheme are being specified. For corrected air flow rates, there are calculated depression residuals $\Delta h_i$ for all the independent contours of the quasi-network model. There is estimated the calculation accuracy.

Step 9: The final result of calculating the air flow rates and branch resistances.

- If $|\Delta h_i| > \varepsilon$, the calculation procedure is repeated until the specified calculation accuracy is achieved. If $|\Delta h_i| \leq \varepsilon$, the calculation ends.

According to this algorithm, a program has been developed that allows predicting air leaks and selecting the most effective way to control gas emissions.

7 Numerical experiments

According to the presented algorithm of calculating air leaks, numerical experiments were carried out with various methods of gas emission control for the mines of the Karaganda coal basin:

- when changing the air flow rate in the longwall face;
- when demolishing ventilation workings;
- when using goaf isolation.

The results of numerical experiments are shown below.

7.1 Changing air flow rates in the longwall face

With this method, various ratios of the amount of air supplied to the longwall face to the amount of air for refreshing were considered. With the ratio equal to 0.4, in the zone where the longwall face meets the ventilation working, the overturning of the ventilation jet was observed in the area up to 20 m. With increasing the amount of air entering the longwall face and decreasing its supply for refreshing (0.7 ratio), the normal ventilation mode of the unstable zone was restored. Further increasing the air supply to the longwall face with simultaneous decreasing its supply for refreshing (1.5 ratio) ensured stabilization of the longwall face ventilation mode that meets safety requirements.

7.2 Ventilation working demolishing

With this method, a supported ventilation working was demolished to the distance of up to 1000 m from the junction with the longwall face. As a result, the ventilation mode of the longwall face junction with the ventilation working deteriorated and air leaks through the collapsed rock massif increased.

7.3 Goaf isolation

When using the goaf isolation from the side of the ventilation working at the distance of up to 200 m from the breakage face, a positive effect was achieved: ventilation of the unstable zone was stabilized, the air flow rate at the exit from the longwall face increased, and the total air leakage through the collapsed rock massif decreased.
Fig. 3 Algorithm of calculating air losses

Start

1. \(Q_{x,i}, Q_{y,i}, S_{x,i}, S_{y,i}, L_{x,i}, L_{y,i}, \xi\)

2. Assignment \(q_i, i=1,2,\ldots,n\)

3. \(\sum q_i \leq Q_x?\)
   - Yes
   - No

   - Account \(\sum q_i > Q_x\)

4. Calculation \(Q_{x,i}, Q_{y,i}, R_{x,i}, R_{y,i}, r_i\)

5. Mathematical description of the analysis based on the first and second laws of networks

6. Calculation of residuals \(\Delta h, i=1,2,\ldots,n\)

7. \(|\Delta h| < \xi?\)
   - No
   - Yes

8. Calculation \(c_i, i=1,2,\ldots,n\)

9. Forming a system of equations for calculating \(\Delta q_i, i=1,2,\ldots,n\)
   - Verification \(q_i^{(k)} = q_i^{(k+1)} + \Delta q_i\)
   - Verification \(Q_{x,i}, Q_{y,i}, R_{x,i}, R_{y,i}, r_i\)

10. Iteration counter

End
8 Results and discussion

The results of numerical experiments have shown that the most effective way to control the air-gas situation in the mining area is to change the ratio of air supply to the longwall face and the ventilation working and to isolate the goaf from the side of the ventilation working. Demolishing of the ventilation working does not improve the ventilation mode of the unstable ventilation zone and contributes to increasing air leaks through the longwall goaf.

When combining all three methods of gas emission control, the ventilation working demolishing also did not have a positive effect on the ventilation of the working area. Thus, this method cannot be recommended as the method for controlling the air-gas situation in working areas, but it can only be recommended for solving technological problems.

9 Conclusions

This paper presents a quasi-network model of the working area with the direct-flow ventilation scheme. On the basis of this model, an algorithm was developed for calculating air leaks through the collapsed rock massif of the goaf. Using the proposed algorithm, three methods of gas emission control used in the mines of the Karaganda coal basin were studied and the most effective ones were determined. The proposed approach to the analysis of the air-gas situation in the working areas allows checking the effectiveness of the selected method of controlling the ventilation mode when using direct-flow ventilation schemes for the working area.

Acknowledgements

The authors would like to thank Zh.G. Levitsky, Dr. Eng., Professor of the Mining Aerology and Occupational Safety Department of Karaganda Technical University (Kazakhstan, Karaganda) for his valuable contribution and supervision of this study.

Declarations

Funding - 'Not applicable'
Conflicts of interest/Competing interests - 'Not applicable'
Availability of data and material - 'Not applicable'
Code availability 'Not applicable'
Ethics approval 'Not applicable'
Consent to participate - 'Not applicable'
Consent for publication - 'Not applicable'

References

Akimbekov A.K., Levitsky Zh.G., Spatayev N.D., Udodov D.B. (1997) Aerodynamics of the mined-out longwall space with the direct-flow ventilation scheme. University Proceedings (Karaganda State Technical University) 2: 162-164
Drizhd I.N., Mashrapov Sh.Zh., Vitebsky Ya.D. (1991) Development of a fire hazardous layer using the direct-flow ventilation scheme. Safety of labor in industry 4: 33-34
Kaliev S.G., Mashrapov Sh.Zh., Zhumashev N.B. (1987) Gas-air mode with the direct-flow ventilation scheme of the working area. Safety of labor in industry 4: 29-30
Levitsky Zh.G. (2013) Mine ventilation networks. LAP LAMBERT Academic Publishing, Germany
Levitsky Zh.G., Nurgaliyeva A.D. (2018) Analyzing and controlling ventilation networks. LAP LAMBERT Academic Publishing, Germany
Tsoi S., Rogov E.I. (1965) Foundations of the theory of ventilation networks. Nauka, Alma-Ata