DOI: https://doi.org/10.1051/e3sconf/202016800049

IDENTIFICATION OF ZONES OF INFLUENCE OF EXOGENOUS FIRE DAMAGING FACTORS

[1]Ivan Kokoulin, [1]Tetiana Bunko, [2]Ihor Yashchenko, [3]Ruslan Papirnyk,
[3]Anatolii Belikov, [4]Vadym Myroshnychenko, [5]Oleksandr Otchenashev

[1]Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, [2]Ministry of Energy and Coal Industry of Ukraine, [3]Prydniprovsk State Academy of Civil Engineering and Architecture, [4]Limited Liability Company "DTEK", [5]InterNations GmbH

Abstract. In this work, topological configuration of dangerous zone in the mine ventilation network and concentrations of fire gases in it are estimated and identified at vent impacting on the emergency conditions. The obtained information on gas-dynamic state of the mine ventilation network at a current moment of time is used for undertaking primary measures according to the plan of accident response: emergency evacuation of people and actions of militarized mine-rescue services for eliminating emergency at its initial stage with taking into account changed emergency ventilation mode. The proposed method allows identifying an area in the mine contaminated by combustion products with taking into account time of its formation, changes in ventilation mode during the accident and possible air stream reversal in zones with descentional ventilation under the influence of the fire source depression and formation of zones with fire gas recirculation. With implementation of this method, it becomes possible to improve accuracy of detecting gassy zones in the ventilation network and effectiveness of emergency response.

Introduction. An exogenous fire in coal mine is one of the most difficult and dangerous types of underground accidents with the greatest number of damaging factors. Among them are changed thermal condition of the fire source and adjacent districts of the mine ventilation network (MVN) and formation of dynamic zones contaminated by gaseous combustion products. Plan of accident response (PAR) provides, as a priority measure, evacuation of all people from the mine, in the first place, from emergency and dangerous (i.e., gas-polluted) districts of the MVN. Therefore, identification of such districts is an indispensable condition for the safety evacuation; minimization of contaminated-by-gas zone θ_z will contribute to increasing its effectiveness [13].

In coal mines, safety rules are limited by the requirement for the people to exit from the emergency zone after they receive a signal about the accident and to go towards a clean district of the MVN following the route of the ventilation stream flowing. The requirement is certainly correct, but it does not contain sufficient information for organizing effective evacuation. If at an emergency, normal mode of ventilation is preserved [1, 2], then zone contaminated with gas, having reached the ventilation shafts, is stabilized, and further information about its configuration can be used for solving the PAR problems. If the ventilation stream reversal is expected, this zone is changing dynamically for some period of time, and therefore, use of emergency evacuation routes significantly depends on the ratio of duration of transition to the reversing ventilation mode and time when evacuation starts. If a fire occurs within an inclined field, then in areas with descentional ventilation, thermal depression of the fire source can provoke reversal of ventilation stream and recirculation of fire gases, which makes it impossible to use the aforementioned requirement.

It is advisable to not include such areas into the routes of emergency evacuation. To this end, their location should be determined as exactly as possible.

It is also necessary to observe the following consideration. A MVN district is considered to be gassy if concentration of conventional carbon monoxide in it exceeds the maximum permissible value. However, this value is commensurate with the accuracy of the control device, even in case of conditionally not-gassy districts in the MVN.

Safety rules recommend for people passing through such districts with self-rescuers on. However, when planning the emergency evacuation routes, they should be avoided whenever it is possible. The presence of the mentioned difficulties in identifying of emergency and dangerous districts in the MVN presents a strong challenge for Ukrainian and foreign researchers [3-8, 12].

In Ukraine, a regulatory document was developed for calculating zones in the MVN contaminated by gaseous combustion products during the fire [2]. However, the results obtained are not always suitable for practical use.

Objective of this work is to determine gassy zones in the ventilation network of a coal mine in case of exogenous fire.

Methods. The method of researches is based on the following main provisions:

a) the existing mathematical model of a MVN presents an aggregate of its branches (i, j), which specify the roadways (their part or aggregate) in the mine, and nodes (crossings of the branches);

b) for each of the branches, length $L(i, j)$, m, and aerodynamic resistance $R(i, j)$ are given, and for the main ventilation fans (MVF), their pressure and productivity are specified;

c) calculations are made for natural air distribution in the MVN, i.e. air consumption and direction of air motion in all roadways of the mine (in the MVN branches) and, consequently, air speed $V(i, j)$, m/s, in them;

d) air distribution in the MVN is calculated for the reversing mode of ventilation;

e) it is considered that district with exogenous fire (branch (i^*, j) is known;

g) it is assumed that debit of gas-air mixture formed in the fire source is zero, i.e. its presence in the ventilation stream is just a quality aspect, which does not change initial air debit in the stream.

Further researches were based on properties of the strongly-connected graph of MVN.

Results and discussion. The following emergency zones can occur in the MVN:

a) gassy zone at normal mode of ventilation θ_n;

b) zone θ_r occurred at reversing mode of ventilation, which, in terms of physics, is similar to zone θ_n ;

c) intermediate gassy zone θ_{in} is formed due to the reversing mode some time after the fire begins. This zone covers roadways, which are clean at normal mode, but become gassy as a result of combustion product reversal from area θ_n existing in the mine from the moment when the fire starts till beginning of realization of emergence ventilation mode.

In order to choose proper ventilation mode, it is necessary to consider special cases of the above-mentioned zones at the last span of time τ with taking into account dynamics of their interaction.

New ventilation mode starts not immediately, but with some delay, which depends on the following factors: moment τ_1 of the fire detecting; time taken for the information transferring to the mine dispatcher and making decision in accordance with the PAR; time τ_2 of the ventilation system inertia; time τ_3 taken for gas draining from zone θ_n appeared during the time $\tau_1 + \tau_2$; and time τ_4 taken for gas draining from a zone appeared as a result of reversal in zone θ_n.

Solving of this problem assumes identifying of all roadways along the ventilation stream motion starting from initial node i^* in the roadway with the fire source, to which gaseous combustion products can get for time period τ.

At the first step, these are all roadways (j^*, j_k), for which:

$$\tau\left(j^*, j_k\right) = \tau - \tau(i^*, j^*) - \frac{L(j^*, j_k)}{V(j^*, j_k)}, \tag{1}$$

where $V(j^*, j_k) = \dfrac{Q(j^*, j_k)}{S(j^*, j_k)}$.

If $\exists\tau(j^*, j_k) > 0$, then $(j^*, j_k) \in \theta_z$ is accepted; node j_k is considered in the same way as the node j^*; in this case, formula (1) is replaced by:

$$\tau(j_k, j_l) = \max \tau(i_k, j_k) - \frac{L(j_k, j_l)}{V(j_k, j_l)}. \tag{2}$$

The calculation is completed when $\forall\ \tau(i_l, j_k) \le 0$. Thus, the gassy zone is presented by:

$$\theta_z : \left\{ (i_k, j_k), \sum_{(i_k, j_k) \in \mu(i^*, i_p)} \frac{L(i_k, j_k)}{V(i_k, j_k)} \le \tau \right\}. \tag{3}$$

The gassy zone reaches its maximal size at the moment:

$$\tau_{\max} = \begin{cases} \tau, & \tau < \tau_5 \\ \max \sum\limits_{(i_k, j_k) \in \mu(i, j_m)} \tau(i_k, j_k), & j_m \in M_1, \quad \tau \ge \tau_5, \end{cases} \tag{4}$$

where τ_5 is time, during which θ_z becomes permanent, and combustion products get the exit from ventilation shafts.

Time, during which the roadway $(i_k, j_k) \in \theta_z$, can be calculated by the formula:

$$\tau'(i_k, j_k) = \tau - \min \sum_{(i_m, j_m) \in \mu(i, i_k)} \frac{l(i_m, j_m)}{V(i_m, j_m)} +$$
$$+ \max \sum_{(i_m, j_m) \in \mu(i', i'')} \frac{L(i_m, j_m) S(i_m, j_m)}{Q(i_m, j_m)} + \frac{L(i_k, j_k) S(i_k, j_k)}{Q(i_k, j_k)}, \qquad (5)$$

where

$$i' \in M'' : \{ j, \forall (i_p, j) \notin \theta_z, \exists (j, j_n) \in \theta_z \}. \qquad (6)$$

Dynamics of gassy zones appeared due to the changed mode of ventilation in the MVN at arbitrary moment of time τ' can be described as follows:

$$\theta_n(\tau') = \begin{cases} \varnothing, & \tau' = 0 \\ \theta_n, & 0 < \tau' \le \tau_1 + \tau_2 \\ \theta_n^{\tau_1 + \tau_2} / \theta_n^{\tau' - (\tau_1 + \tau_2)}, & \tau_1 + \tau_2 < \tau' \le \tau_3 \\ \varnothing, & \tau' > \tau_3 \end{cases} \qquad (7)$$

$$\theta_r(\tau') = \begin{cases} \varnothing, & 0 \le \tau' + \tau_1 + \tau_2 \\ \theta_r^{\tau' - (\tau_1 + \tau_2)}, & \tau_1 + \tau_2 < \tau' < \tau_5 \\ \theta_r, & \tau' \ge \tau_5 \end{cases} \qquad (8)$$

$$\theta_{in}(\tau') = \begin{cases} \varnothing, & 0 \le \tau' + \tau_1 + \tau_2 \\ \theta_{in}^{\tau'}, & \tau_1 + \tau_2 < \tau' < \tau_4 \\ \theta_r, & \tau' \ge \tau_4 \end{cases} \qquad (9)$$

where Ø is an empty set.

The researches show that if τ_1 is great enough, zone θ_{in} can cover a great volume of roadways. Consequently, while studying efficiency of a ventilation mode, it is necessary to compare sizes of zones $\theta_n(\tau)$ and $\theta_n^{\tau_1 + \tau_2} \cup \theta_{in}^{\tau_4} = \theta_v$ (if $\tau_4 > \tau$, the latter zone is replaced by zone θ_p) instead of zones θ_n and θ_r.

Zone $\theta_n^{\tau_1 + \tau_2} \cup \theta_{in}^{\tau_4} = \theta_v$ can be considered as a temporally gassy zone in the MVN. While studying dynamics of gassy zones in the MVN at the ventilation stream reversal, the key task is to analyze sizes and duration of gas draining from zone θ_z. The latter is determined by the formula:

$$\tau_r = \max \{ \tau_3, \tau_4 \}. \qquad (10)$$

Since gaseous combustion products move within zone θ_b along the routes from the nodes in the upper boundary of zone θ_b (to which gaseous products have got by the moment when reversing ventilation mode is set) towards nodes in the lower boundary, therefore, when fresh-air streams reach lower boundary of zone θ_b, which coincides with the boundary of zone θ_p, it means that gas is drained from the zone θ_b.

Nodes in the upper boundary of zone θ_b make the quantity M'', which is determined from formula (6) when $\theta_z = \theta_b$; the upper boundary of this zone is determined as:

$$M' : \{j, \forall(j, j_k) \in \theta_r, \exists(i, j) \notin \theta_r\}. \tag{11}$$

Then

$$\tau_r = \max\left\{ \sum_{(i_k, j_k)\in\mu(i,j)} \frac{L(i_k, j_k)}{V(i_k, j_k)},\ (i_k, j_k) \in \mu(i, j), i \in M_2, j \in M_1 \right\}. \tag{12}$$

Method for calculating τ_r is the following: for the nodes $i_k \in M''$, (i_k, j_k) are determined and $\tau(i_k, j_k)$ are calculated. The same is performed for the node j_k, i.e. at each step, a parameter to be calculated for the end nodes of the roadway under consideration is gas-draining duration in the maximally long route from $i_k \in M''$ to this node. When j_k is considered as $\forall_j \in M''$, maximal value of this parameter determines value of τ_r.

Modeling of gassy zones in the MVN assumes stable air motion in all districts of the MVN, including emergency and dangerous areas. In other words, when emergency ventilation mode is realized, it is assumed that ventilation stream reversal in the MVN roadways is determined exceptionally by the change (changed sign) of the MVF depression and (or) change of $R(i, j)$ in devices for local regulation of ventilation streams. Concentration field moves away from the place of fire i^* towards return shafts.

When the regulation is completed, concentration field, for the purpose of realizing emergency ventilation mode, remains static during the whole period of the fire suppression (of course, if $C(i^*, j) = const$), and concentrations of fire gases in the nodes along the routes of the ventilation stream moving is calculated by the formula:

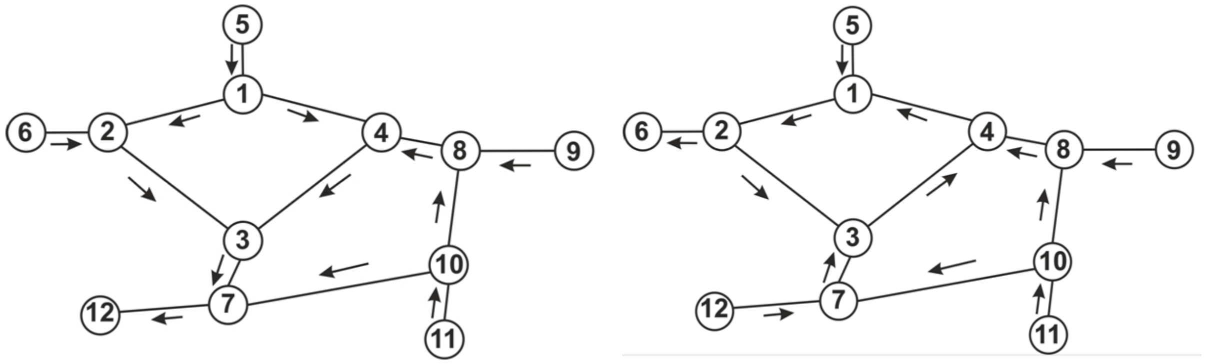
$$C_i = \sum C(j_k, i) Q(j_k, i) \left[\sum Q(j_k, i)\right]^{-1}. \tag{13}$$

However, this situation can be simulated with absolute certainty only when fire occurs in horizontal or slightly-inclined districts of the MVN.

In case of fire with heat release, ventilation stream reversal in the inclined or vertical roadway with descending ventilation or in roadways adjoining to it [9] is possible with formation of recirculation contour, i.e. aggregate of roadways with circular motion of air stream [8, 10, 11]. In total case, there may be several such contours. They form a recirculation zone being a part of the gassy zone.

There can be two types of recirculation contours in the MVN: contour of direct recirculation, which includes roadway with the fire source, and contour of indirect recirculation, which is under the effect of thermal depression of the fire source only.

Example of formation of direct recirculation contour is shown in Figure 1.



a b

Figure 1 – Formation of contour of direct recirculation: a – directions of air stream before the fire, b – stream reversal in the roadway during the fire

Directional field of air streams in the chosen district of the MVN is shown in Figure 1a. In case of fire in the roadway (4,3) when $H_3 < H_4$, the roadway depression gradually reduces (thermal depression counteracts in the fans) with further spread of the fire, and ventilation stream reverses (Fig. 1b). Contour of direct recirculation K_n: {(1,2), (2,3), (3,4), (4,1)} is formed.

If to accept $C(3,4)$ as a constant and equal to C, then concentration in the rest roadways within the contour can be calculated by formula (13). The $C(3,4) \neq C(2,3)$ can be considered as a solution of the direct recirculation problem.

Let's consider contour of indirect recirculation shown in Figure 2.

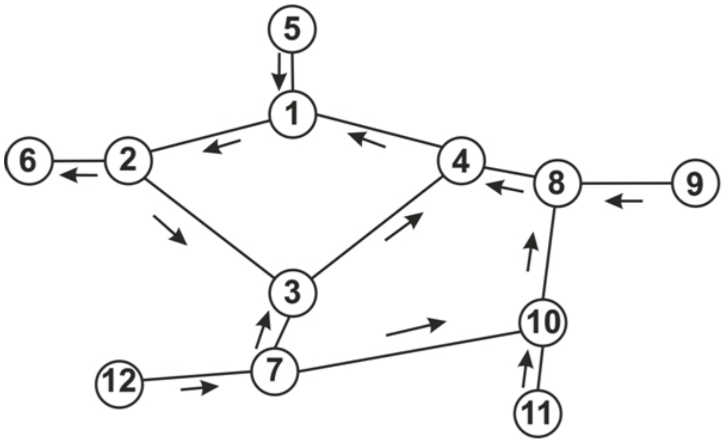


Figure 2 – Formation of contour of indirect recirculation (stream reversal in two roadways during the fire)

Directional field of air streams before the fire is represented in the Figure 1a. In case of fire in roadway (7,12) when $H_{12}<H_7$, stream reversal occurs in the roadway (3,7) and causes formation of the contour K_k :{(1,2), (2,3), (3,4), (4,1)} shown in Figure 1b. Only one roadway (7,3) enters the contour from outside; it contains gaseous products with the following concentration:

$$C(7,3) = \frac{CQ(12,7)}{Q(12,7) + Q(10,7)} = C_1 \tag{14}$$

However, afterwards, the roadway (2,3) will be appeared to be gassy as well causing change of the *C*(3,4) and, in its turn, of the *C*(2,3). The described phenomenon makes it impossible to use formula (13) for calculating concentration of gaseous products in the recirculation contour.

Making calculations for a general case when recirculation contour consists of *k* roadways, we get that at *n* step of the iteration process, concentration of gaseous products in the first roadway of contour [(roadway (i_1, j_1), into which gaseous products flow directly from the fire source, is considered as the first; in the described case, (3,4) is the first roadway of contour)] can be define as:

$$C\ (i_1, j_1) = C_1 Q_1 \sum_{p=1}^{n} \left[\prod_{i=1}^{k} \sum Q(i', j_i)^{p-1} \left(\prod_{i-1}^{k} \sum Q(i', i)^{n-p} \right) \right] \left[\sum Q(i', j_i)^{n} \left(\prod_{i=2}^{k} \sum Q(i', i)^{n-1} \right) \right]^{-1}, \quad (15)$$

where C_1, Q_1 is concentration of gaseous products and air debit in the roadway that feeds gaseous products from the fire source to the first roadway of the recirculation contour.

Nodes of the contour are numbered starting from the first node of first roadway.

The iteration process is converging if:

$$\left| C^{n+1}(i_1, j_1) - C^{n}(i_1, j_1) \right| < \left| C^{n}(i_1, j_1) - C^{n-1}(i_1, j_1) \right|. \quad (16)$$

Putting of values $C^{n+1}(i_1, j_1), C^{n}(i_1, j_1), C^{n-1}(i_1, j_1)$ into (16) transforms it into:

$$\prod_{i=1}^{k} Q(i_1, j_1) \prec \prod_{i=1}^{k} \sum Q(i', i). \quad (17)$$

The latter is obvious because strict inequality can be broken only if no roadways enter the recirculation contour from outside. It means that the process is a converging one, and criterion for estimating it convergence is a value of deviation between results of two consecutive iterations. When it becomes less than ε (exactness of calculation), a value chosen from the practical considering, the calculation is considered completed.

However, in more general case, recirculation contour can occur in any point of gassy zone and can contain some nodes with gaseous product inflow. In Figure 2, a case is shown when as a result of fire in the roadway (12,7), the stream reverses not only in the roadway (7,3), but in the roadway (7,10) as well. Gaseous products enter the recirculation contour through the node 4, making impossible to use formula (8). The researches show that for the case under consideration, concentration of gases in the first roadway of contour is determined as:

$$C^n(i_1, j_1) = \frac{\sum C(i', j_1)Q(i', j_1)\left(\prod_{i=1}^{k}\sum Q(i',i)^{n-1}\right)}{\left(\sum Q(i',i_1)^n\right)\left(\prod_{i=2}^{k}\sum Q(i',i)^{n-1}\right)} +$$

$$+\frac{\sum_{p=1}^{k}\sum C(i',i_p)Q(i',i_p)\sum_{j=1}^{n-1}\left[\prod_{l=1}^{p}Q_j(i_l, j_l)\left(\sum (Q(i',i_l)^{n-j-1})\right)\right]}{\left(\sum Q(i', j_i)^n\right)\left(\prod_{i=2}^{k}\sum Q(i',i)^{n-1}\right)} \times \prod_{l=p+1}^{k} Q^{i-1}(i_l, j_l)\left[\sum Q(i', j_l)\right]^{n-j}. \tag{18}$$

After the needed transformations are made, we get:

$$\lim_{n\to\infty} C^n(i_1, j_1) = \frac{C_1 Q_1}{\sum Q(i', j_1)} \frac{\prod_{i=1}^{k} Q(i',i)}{\prod_{i=1}^{k} Q(i',i) - \prod_{i=1}^{k} Q(i_i, j_i)}. \tag{19}$$

The first factor in formula (19) is analogous to (13), and the second is always a finite number, from which we can conclude that there is no endless growth of the fire gas concentration in roadways within the recirculation contour.

Use of formula (19) instead of (15) for calculating concentration in the first roadway of the recirculation contour eliminates the need for intuitive specifying of *n*, therefore, formula (12) is more accurate and justified.

The proposed method can be illustrated by the example of calculation of recirculation contour (4,11), (11,8), (8,7), (7,6), (6,4) (Fig. 3).

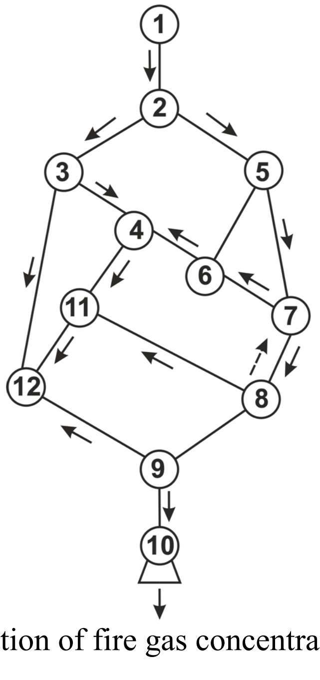


Figure 3 – Example of calculation of fire gas concentration in the recirculation contour

Initial data for the calculation are shown Table 1.

The recirculation contour appears due to the stream reversal in the roadway (7,8).

The node entering the recirculation contour is 4, and the first roadway is (4,11). The gassy zone formed according to the method described above includes roadways (3,4), (4,11), (11,8), (8,7), (7,6), (6,4), (11,12), (12,9), (8,9), (9,10). By applying formula (12), we get:

$$C(4,11)=\frac{5.0\cdot 15.0}{15.0+10.0}\,\frac{(15+10)\cdot 25\cdot 15\cdot(4+1)\cdot 10}{25\cdot 25\cdot 15\cdot 5\cdot 10-25\cdot 3000}=3.57. \qquad (20)$$

With the help of formula (7), we further get: $C(11,12)=C(11,8)=3.57$; $C(12,9)=0.92$; $C(8,9)=C(8,7)=3.57$; $C(7,6)=2.86$; $C(6,4)=C(6,4)=1.43$; $C(9,10)=1.5$.

For the purpose of verification with taking into account the obtained results, it is possible to calculate:

$$C(4,11)=\frac{1.43\cdot 10\cdot 5\cdot 15}{10+15}=3.57. \qquad (21)$$

Such significant concentrations of carbon monoxide in roadways of the gassy zone are taken artificially, only for clarity of calculations; in reality, they are much smaller and in many cases are commensurable with the accuracy of the control devices

Table 1 – Initial data for calculation of gas concentrations in the recirculation contour[*]

Initial node *i*	Last node *j*	*Q*(*i*, *j*)	
		before fire	during the fire
1	2	50.0	50.0
2	3	44.0	44.0
2	5	6.0	6.0
3	4	34.0	15.0
6	4	2.0	10.0
4	11	36.0	25.0
11	8	7.0	15.0
7	8	4.0	4.0[**]
7	6	1.0	5.0
5	6	1.0	5.0
5	7	5.0	1.0
3	12	10.0	29.0
12	9	39.0	39.0
8	9	11.0	11.0
9	10	50.0	50.0
11	12	29.0	10.0

[*] Concentration of gases before the calculation beginning is equal to 5

[**] During the fire (8, 7)

Conclusions. Thus, the most general solution to the problem of determining gassy zones in the MVN of a coal mine in the event of an exogenous fire is obtained. The solution allows getting results for both unchanged and reversing emergency ventilation modes with taking into account effect of thermal depression on stability of ventilation streams. The solution is both qualitative and quantitative as it allows assessing not only the risk of emergency evacuation of people during an accident, but also the degree of this risk, which means to choose and quantitatively assess feasibility of implementation of the chosen ventilation mode with taking into account not only minimization of fire factor impact, but also improvement of safety for as many working people as possible. The solution does not depend on specific conditions of a particular mine; therefore, it can be recommended for wide-scale implementation.

REFERENCES

1.Bolbat, I.Ye., Lebedev, V.I., Trofimov, V.A. (1992). *Avariynye ventilyatsionnye rezhimy v ugolnykh shakhtakh*, Moskva: Nedra

2.Ministry of Power Engineering and Coal Industry of Ukraine (2003), DSTU 10.1-00174102-008-2003 *Zony zagazuvannya girnychykh vyrobok vugilnykh shakht produktamy termodestruktsii vid pidzemnykh pozhezh Metodyka rozrakhunku* [SSTU 10.1-00174102-008-2003. Zones of the gassy of mine workings of coal mines by the products of thermodestruction from underground fires. Method of calculation], Kyiv, UA

3.John C. Edwards, Rudolf E. Greuer. (1982). Inf. Circ. Bur. Mines US Dep. Inter., 8901, 117

4.Wasilewsky, S. (1997). Arch. Mining sci., **42, (**1), 45-62

5.Levin, L.Yu., Kormshchikov, D.S., Syemin, I.A. (2013). *Resheniye zadachi operativnogo rascheta raspredeleniya produktov goreniya v seti gornykh vyrabotok*, *Gorny informatsionno-analitichesky byulleten*, (12), 179-184

6.Wu Chao, J. Ant. – S. Inst. Mine and Met., **21**, (5), 460-466 (1990)
https://doi.org/10.1080/02331889008802255

7.Dziuerzynsky, W., Kravszuk, J. (2001). Arch. Mining Sci*.,* **46**, (2), 119-137

8.Dziuerzynsky, W., Palka, T. (2001). Arch. Mining Sci., **46**, (2), 103-118

9.Wang De-ming, Zhou Fu-bao. (2003). J. China Univ. Mining and Technol., **32**, (3), 227-231

10. Krasnoshtein, A.Ye., Kazakov, B.P., Shalimov, A.V. (2006). Modelirovaniye nestatsionarnykh protsessov rasprostraneniya gazovykh primesey po vyrabotkam v usloviyakh retsircukyatsionnogo provetrivaniya, *Phiziko-tekhnicheskiye problemy razrabotki poleznykh iskopayemykh*, **1**, 95-101

11. Vassel, R.Ya. (1974). Opredeleniye ventilyatsionnykh parametrov pri retsirkulyatsii vozdukha v vyrabotkakh s nepreryvnymi vydeleniyami vrednjstey, *Ventilyatsiya shakht i rudnikov*, **1**, 54-59

12. Popov, V.A., Pisarev, Yu.N., Ulyanov, V.M. (1973). Opredeleniye zon zagazirovaniya pri pozharakh, *Tekhnika bezopasnjsti, okhrana truda i gornospasatelnoye delo*, **5**, 25-27

13. Mineev S.P., Smolanov S.N., Belikov I.B., Samopalenko S.N. Obosnovanie vybora avariynykh ventilyatsionnykh rezhimov pri tushenii pozharov (2018), *Modern Scientific Researchers*, **5**, 16-21