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Article

Airflow sensitivity assessment based on the underground mine ventilation systems modeling

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Abstract: This paper presents a methodology for determining the sensitivity of the main air flow directions in ventilation subnetworks to changes of aerodynamic resistance and of air density in mine workings. Formulae for determination of the sensitivity of the main subnetwork air flows by establishing the degree of dependency of the air volume stream in a given working on the variations in resistance or air density of other workings of the network have been developed. They have been implemented in the *VentGraph* mine ventilation network simulator. This software, widely used in Polish collieries provides an extended possibility to predict the process of ventilation, air distribution and, in the case of underground fire, also the spread of combustion gasses. The new method facilitates assessment by mine ventilation services of the stability of ventilation systems in exploitation areas and determine of the sensitivity of the main subnetwork air flow directions to changes of aerodynamic resistance and air density. Recently in some Polish collieries new longwalls are developed in seams located deeper then the bottom of the intake shaft. Such solution is called “exploitation below the level of access” or “sublevel”. The new approach may be applied to such developments to assess the potential of changes of direction and air flow rates. In addition, interpretation of the developed sensitivity indicator is presented. While analyzing air distributions for sublevel exploitation, application of current numerical models for calculations of the distribution results in tangible benefits, such as the evaluation of the safety or risk levels for such exploitation. Application of the *VentGraph* computer program, and particularly the module *POŻAR (fire)* with the newly developed options, enables an additional approach to the sensitivity indicator in evaluating air flow safety levels for the risks present during exploitation below the level of the intake shaft. The analyses performed and examples presented enabled useful conclusions in mining practice to be drawn.

Keywords: ventilation process prediction; safety of mine ventilation system; sensitivity of the main air flows in ventilation subnetworks

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1. Introduction

New possibilities for calculation tools enabling mine ventilation services to determine safety indices for the operation of a ventilation system based on a system of *VentGraph* computer programs have been presented [3], [4], [5], [6]. The system of *VentGraph* programs is used in a number of Polish coal mines, as well as in Australian, North American, Vietnamese and Czech coal mines [8], [15]. At the same time a systematic use of 2D and 3D dimensional flow modelling [13], [14], [16] resulting from new development of the Computational Fluid Dynamics provides insight, which is more detailed but limited to one or a few workings. So far modelling large ventilation systems is practically possible only with one dimensional flow approximation, used by programs like Ventgraph, which justifies their further development. The results thus obtained open new possibilities for study and analysis, particularly of phenomena caused by the methane inflow to areas of mining longwalls and goaf.

Good results in terms of the assessment of ventilation system operational safety are obtained with an analysis of ventilation systems based on stability indicators, which when supplemented with a

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sensitivity assessment of the local area air flows, brings interesting elements to the evaluation of natural risks.

The subject of the stability of flows bringing air to the longwall is of utmost importance. In the event of fire, weak and unstable air flows pose the risk of reversed flow. Stability of ventilation in exploitation areas is important not only for underground fires, but also while ventilating zones of methane hazard [1], [15]. Changes in ventilation conditions in those zones may lead to a build-up of hazardous methane concentrations at the workplace. This results not only from the lack of a sufficient air volume needed to dilute the methane, but is also due to the gaseous dynamic processes present at the longwalls. The vital issue while ventilating mining areas is the variability in time for the output of the existing methane sources, which depends largely on the exploitation advance and ventilation conditions. Ventilation disturbances cause the air volumes migrating through the goaf to change and, consequently, result in changes of methane quantities released from the goaf. Liberation of methane from the worked out area (goaf) is one of the most variable and difficult to control methane sources at the longwall, the activity of which depends mainly on the stability of air flow through the area. Therefore, the problem of the possible flow irregularities apparent in changed air output and its flow directions in specific branches of the ventilation network is of utmost importance for the fire and methane safety of every mine.

A useful addition to the evaluation of air flow stability is the determination of the indices of the sensitivity of the main flows in ventilation subnetworks to the changes of aerodynamic resistance of workings [10], [11], [12]. This parameter shows the degree of dependency of air volume stream in a given working to the resistance of other workings forming the network. Recently in some Polish collieries new longwalls are developed in seams located deeper then the bottom of the intake shaft. Such solution is called "exploitation below the level of access". For ventilation subnetworks located below the level of access, it is important to study the potential for changes of the stream volume and fire gasses when a fire develops. Therefore, a new approach is proposed to the subject of air flow assessment in workings below the level of access, and formulas are developed for determination of the sensitivity of local air flows for the change (decrease) of air density.

For the formulae and equations presented, algorithms are proposed, based on which new procedures for the *VentGraph* program have been developed [5]. Examples are presented to illustrate the performance of new calculation capacities of the *VentGraph* program. The results prove their usefulness for analyzing the changes of air flow direction and distribution in a ventilation system of an underground mine.

2. Calculation of airflows in workings of a mine ventilation network with the *VentGraph* software

The mine ventilation system may be represented as a network, in which shafts, galleries and longwalls are branches and places where they intersect are nodes. Then the flow distribution may be calculatated from following system of matrix equations:

- equation of the mass flows balance in the network nodes (Kirchhoff's First Law)

$$\mathbf{a} \cdot \mathbf{q} = \mathbf{0} \tag{1}$$

- equation of pressure balance for independent loops (circuits) of ventilation network (Kirchhoff's Second Law)

$$\mathbf{b} \cdot \mathbf{p} = \mathbf{0} \tag{2}$$

- equation linking the air mass streams in branches with loop streams

$$\mathbf{q} = \mathbf{b}^{\mathrm{T}}\mathbf{Q} \tag{3}$$

where **a** - matrix of node-branch incidence of I x J dimension,
$a_{i,j} = 1$ - branch j is oriented towards node i,
$a_{i,j} = -1$ - branch j is oriented from node i,
$a_{i,j} = 0$ - node i is not a node of branch j,

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b - matrix of loop-branch incidence of K x J dimension,
$b_{k,j} = 1$ - loop k contains branch j, and the branch and loop orientations are consistent,
$b_{k,j} = 1$ - loop k contains branch j, and the branch and loop orientations are opposite,
$b_{k,j} = 1$ - loop k does not contain branch j,
I - number of network nodes,
J - number of branches in the network,
K - number of independent loops in the network, $K = J - I + 1$,
q - column matrix of air mass streams in branches $q_{m\,j}$ of dimension J,
p - column matrix of branch pressure differences Δp_j of dimension J,
Q - column matrix of loop air mass streams Q_k of dimension K
0 - column zero matrix of dimension J.

The difference in branch pressures Δp_j for branch j is given by the formula [17]:

$$\Delta p_j = p_{0\,j} - p_{L\,j} = \left(R_{b\,j} + R_{l\,j}\right) q_j \left|q_j\right| - g\rho_{av\,j}\left(z_{0\,j} - z_{L\,j}\right) - h_{w\,j} \tag{4}$$

where $p_{0\,j}$, $p_{L\,j}$ - static pressures at the beginning and at the end of branch j,
q_j - air volume stream in branch j,
$R_{b\,j}$ - aerodynamic resistance of branch j,
$R_{l\,j}$ - local aerodynamic resistance in branch j (e.g. a ventilation door),
g - acceleration of gravity,
$\rho_{av\,j}$ - average air density in branch j,
$z_{0\,j}$, $z_{L\,j}$ - elevation of the beginning and of the end of branch j,
$h_{w\,j}$ - pressure of a fan (if present) in branch j .

Aerodynamic resistance of branch R_b and local aerodynamic resistance R_l for the air mass stream are given by formulae:

$$R_b = \frac{\lambda P L}{8\rho_{av} A^3} \quad \text{and} \quad R_l = \frac{\zeta}{2\rho_{av} A^2} \tag{5}$$

where λ, ζ - dimensionless coefficients of the branch resistance and of the local resistance,
ρ_{av} - average air density in the branch,
A - area of branch cross-section,
P - circumference of the branch cross-section,
L - length of the branch.

There is a relationship between air mass stream q and volume stream q_V

$$q = \rho_{av} q_V \tag{6}$$

The average air density in the branch is given by the formula:

$$\rho_{av} = \frac{p_{av}}{T_{av} \sum_{n=1}^{N} \Re_n C_{M\,n}} \tag{7}$$

where p_{av} - average atmospheric pressure in the branch $p_{av} \approx \frac{p_0 + p_L}{2}$
p_0, p_L - atmospheric pressures at the beginning and at the end of the branch,
T_{av} - average air temperature (in K) in the branch $T_{av} \approx \frac{T_0 + T_L}{2}$
T_0, T_L - air temperature at the beginning and at the end of air split,
$\Re_n$ - gas constant of n-th air component,
$C_{M\,n}$ - mass fraction of n-th air component.

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The ***Ventgraph*** software, developed at the IMG-PAN [5], is a typical representative of computer software, in which a numerical method for airflow distribution is based on the Kirchhoff's Second Law (2). The algorithm of the steady state computation is based the one-dimensional mathematical model of air flow in the network, given above. This model is based on the equation describing the air flow in ventilation network branches (4), (5), [17]. The software adopts a numerical algorithm for this system solution based on the modified Euler method, provided by Hardy Cross [2], [9], [18]. It is necessary to emphasise here, that the adopted mathematical model of flow takes into account changes of air density caused by changes of atmospheric pressure and caused by changes of air composition and of temperature (4), (5), (7). As a result, most phenomena, which could affect the airflows the network, have been considered.

The software algorithm contains a number of possibilities related to the regulation of the ventilation network (calculations of the ventilation door resistance value or of the auxiliary fan pressure), including the control of network condition, and designing new workings, etc. The software contains an interactive graphical user interface. Results of calculations are presented in an isometric diagram of specific ventilation network.

3. Sensitivity of local area air flows

An important parameter for evaluation and analysis of the ventilation systems is the sensitivity of local area air flows. This parameter shows the degree of sensitivity of an air volume stream in a given working to disturbances in the workings forming the network. In the study, it has been assumed that the disturbances can be resistance changes of ventilation branches and air density variations in those branches as a result of fire or methane inflow.

3.1. Indicator of volume stream sensitivity in branch i to resistance change in branch j

The volume stream sensitivity in branch *i* to resistance changes in the ventilation network branches can be determined with the aid of the **resistance sensitivity indicator**, defined as follows [11], [12]:

$$\varepsilon_{i,j} = \frac{\partial q_{V\,i}}{\partial R_j} \tag{8}$$

where: q_{Vi} – air volume stream in branch *i*;

R_j – aerodynamic resistance in branch *j*.

The resistance sensitivity indicator shows, how the air stream in branch *i* changes due to the changed resistance of branch *j*. The higher is the indicator's absolute value, the higher is the change of air stream in branch *i* resulting from the change of branch *j* resistance. Indicator's sign shows the direction of change (decrease for negative) .

A good approximation of this derivative value $\partial q_{V\,i} / \partial R_i$ in the surroundings R_j is the following expression:

$$\frac{\partial q_{V\,i}}{\partial R_j} = 2a_{2\,i,j} R_j + a_{1\,i,j} \tag{9}$$

where $a_{R\,i,j}$ and $b_{R\,i,j}$ are factors of the parabola estimating the dependency $q_{V\,i} = f(R_j)$:

$$q_{V\,i} = a_{2,i,j} R_j^2 + a_{1,i,j} R_j + a_{0,i,j} \tag{10}$$

Calculation of those factors requires the solution of the ventilation network for three resistance values R_j:

$$q_{V\,i,1} = f(R_{j,1}) \qquad q_{V\,i,2} = f(R_{j,2}) \quad q_{V\,i,3} = f(R_{j,3}) \tag{11}$$

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Now, the factors $a_{0,i,j}$, $a_{1,i,j}$ and $a_{2,i,jj}$ can be calculated by solving the system of equations, which takes the following form in matrix notation:

$$\mathbf{Q} = \mathbf{R}\,\mathbf{A} \tag{12}$$

where

$$\mathbf{Q} = \begin{bmatrix} q_{V\,i,1} \\ q_{V\,i,\,2} \\ q_{V\,i,3} \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} R_{j,1}^2 & R_{j,1} & 1 \\ R_{j,2}^2 & R_{j,2} & 1 \\ R_{j,3}^2 & R_{j,3} & 1 \end{bmatrix}, \qquad \mathbf{A} = \begin{bmatrix} a_{2,i,j} \\ a_{1,i,j} \\ a_{0,i,j} \end{bmatrix}. \tag{13}$$

This system solution has the form

$$\mathbf{A} = \mathbf{R}^{-1}\mathbf{Q} \tag{14}$$

$$\text{where} \qquad \mathbf{R}^{-1} = \frac{1}{D_R}\mathbf{K} \tag{15}$$

Determinant D_R equals

$$D_R = R_{j,1}^2 R_{j,2} + R_{j,2}^2 R_{j,3} + R_{j,3}^2 R_{j,1} - R_{j,3}^2 R_{j,2} - R_{j,2}^2 R_{j,1} - R_{j,1}^2 R_{j,3} \tag{16}$$

and **K** is the matrix of cofactors of the transpose of matrix, $\mathbf{R}^T$

The factors $a_{1,i,j}$ and $a_{2,i,j}$ calculated from (14) equal:

$$a_{R\,i,j} = \frac{K_{1,1}q_{V\,i,1} + K_{1,2}q_{V\,i,2} + K_{1,3}q_{V\,i,\,3}}{D_R} \tag{17}$$

$$b_{R\,i,j} = \frac{K_{2,1}q_{V\,i,\,1} + K_{2,2}q_{V\,i,\,2} + K_{2,3}q_{V\,i,\,3}}{D_R} \tag{18}$$

Matrix cofactors in the formulas (17) and (18) equal:

$$\begin{aligned} &K_{1,1} = R_{j,2} - R_{j,3} \quad K_{1,2} = R_{j,3} - R_{j,1} \quad K_{1,3} = R_{j,1} - R_{j,2} \\ &K_{2,1} = R_{j,3}^2 - R_{j,2}^2 \quad K_{2,2} = R_{j,1}^2 - R_{j,3}^2 \quad K_{2,3} = R_{j,2}^2 - R_{j,1}^2 \end{aligned} \tag{19}$$

Having calculated the factors $a_{1i,j}$ and $a_{2i,j}$ from the formulae (17) and (18), from formulae (5) and (9), the resistance sensitivity indicator showing the air volume stream sensitivity in branch *i* to the change of resistance in branch *j* can be calculated.

$$\varepsilon_{i,j} = \frac{A_{R\,j,1}q_{V\,i,1} + A_{R\,j,2}q_{V\,i,2} + A_{R\,j,3}q_{V\,i,3}}{D_{R\,j}} \tag{20}$$

where: $q_{V\,i,1}$, $q_{V\,i,2}$, $q_{V\,i,3}$ – air volume streams in branch *i* calculated for resistance values R_{j1}, R_{j2}, R_{j3} of branch *j*.

Values of the factors $A_{R\,j,1}$, $A_{R\,j,2}$, $A_{R\,j,3}$ are determined by the formulae:

$$\begin{gathered} A_{R\,j,1} = 2R_j K_{R\,j,1,1} + K_{R\,j,2,1}, \qquad A_{R\,j,2} = 2R_j K_{R\,j,1,2} + K_{R\,j,2,2}, \\ A_{R\,j,3} = 2R_j K_{R\,j,1,3} + K_{R\,j,2,3} \end{gathered} \tag{21}$$

For resistance values of branch *j* expressed as a fraction u_R, the following computational formulae were developed. In calculations, the following resistance for branch *j* is assumed:

$$R_{j,1} = R_j, \quad R_{j,2} = R_j + \Delta R, \quad R_{j,3} = R_j - \Delta R \tag{22}$$

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Let ΔR be some fraction u_R of the resistance value R_j then:

$$R_{j,2} = (1+u_R)R_j\,, \quad R_{j,3} = (1-u_R)R_j \tag{23}$$

where R_j – aerodynamic resistance in branch j.
The resistance sensitivity indicator equals:

$$\varepsilon_{i,j} = \frac{q_{V\,i,\,2} - q_{V\,i,\,3}}{2u_R R_j} \tag{24}$$

The solution of a ventilation network for two resistance values R_j enables calculation of sensitivity indicator [$\varepsilon_{i,j}$] for all sensitivity indicator located in column j of the sensitivity indicator matrix with dimensions J x J, where J is the number of branches in the ventilation network.

3.2 Interpretation of the sensitivity indicator in terms of resistance change in the branch

Having analyzed the indicators of air volume stream sensitivity to resistance changes in branches calculated for a ventilation network in terms of the value module and sign, it may be concluded that:

- A negative sign for the indicator corresponds to the basic dependency between the air volume stream and aerodynamic resistance, i.e. the volume stream decreases with an increase in the branch resistance.
- The module of indicator values enables selection of the branches in which the resistance change considerably affects the volume stream in a selected branch, i.e. parameters significant for the network regulation.

For example, when the indicator of air volume stream sensitivity in branch i to resistance change in branch j equals $\varepsilon_{i,j} = -2$, it means that an increase of resistance in branch j of 10% will cause the volume stream value in branch i to decrease by approximately 20%. The approximation results from the fact that the dependency between the air stream volume in branch i and the resistance in branch j is not linear.

3.3. Indicator of volume stream sensitivity in branch i to air density change in branch j

Similarly to the branch resistance, the **density sensitivity indicator** showing the volume stream sensitivity in a branch to air density changes in the ventilation network may be defined:

$$\kappa_{i,j} = \frac{\partial q_{V\,i}}{\partial \rho_j} \tag{25}$$

where: q_{Vi} – air volume stream in branch i; ρ_j – air density in branch j.

The indicator of sensitivity to air density change is calculated in the same way as the indicator of sensitivity to branch resistance change, with the difference that in formulae (9), (10) and (11) the resistance of j-th branch R_j is replaced with the air density in this branch ρ_j, and formula (12) takes the form:

$$\mathbf{Q} = \mathbf{G}\,\mathbf{A} \tag{26}$$

where matrix **G** equals

$$\mathbf{G} = \begin{bmatrix} \rho_{j,1}^2 & \rho_{j,1} & 1 \\ \rho_{j,2}^2 & \rho_{j,2} & 1 \\ \rho_{j,3}^2 & \rho_{j,3} & 1 \end{bmatrix} \tag{27}$$

For calculations, the following air density values may be assumed for branch j:

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$$\rho_{j,1} = \rho_j , \quad \rho_{j,2} = \rho_j + \Delta\rho , \quad \rho_{j,3} = \rho_j - \Delta\rho \tag{28}$$

Let $\Delta\rho$ be some factor u of air density value ρ_j then:

$$\rho_{j,2} = (1 + u_\rho)\rho_j , \quad \rho_{j,3} = (1 - u_\rho)\rho_j \tag{29}$$

where: ρ_j – aerodynamic resistance in branch j.

The density sensitivity indicator equals:

$$\kappa_{i,j} = \frac{Q_{V\,i,j,2} - Q_{V\,i,j,3}}{2u_\rho \rho_j} \tag{30}$$

The solution of a ventilation network for two air density values ρ_j enables calculation of density sensitivity indicator [$\kappa_{i,j}$] for all network branches in column j of the sensitivity factor matrices with dimensions J x J, where J is the number of branches in the ventilation network.

3.4 Interpretation of the sensitivity indicator in terms of air density changes

Having analyzed the indicators of air volume stream sensitivity to air density changes in the branches in terms of the value module and sign, it may be concluded that:

- A positive sign for the indicator means an increase in the air volume stream value in the branch together with an increase in air density in a different branch, and a decrease in the stream value with decreasing air density in another branch.
- A decrease in air density in a working occurs in the case of fire or methane inflow.
- The module of indicator values enables selection of the branches in which the air density change considerably affects the volume stream in a selected branch. In combination with a positive sign for the indicator, this may indicate the possibility of reversing the air flow direction.

For example, when the sensitivity indicator of the air volume stream in branch i to air density change in branch j is $\kappa_{i,j} > 2$, this means that, in branch i, there is the probability of reversing the air flow direction. The limit value of the indicator $\kappa_{i,j} = 2$ results from the assumption that the air density value in the case of fire in branch j could drop by as much as 50%, and would be accompanied by an air volume stream reduction in branch i of as much as 100%.

4. New procedures with the *VentGraph* program

The above formulae, enabling the determination of the sensitivity of local area air flows, have enabled development of a series of new procedures for the *VentGraph* program.

In the GRAS module of the *VentGraph* program, a new option—'Indicators'—has been added. This includes a sub-option for calculation of a sensitivity indicator for a selected branch. Functions of the new procedures of the program are shown in Fig. 1 for example in the area of longwall F-3 under liquidation, and the F-4 longwall in the reinforcement phase.

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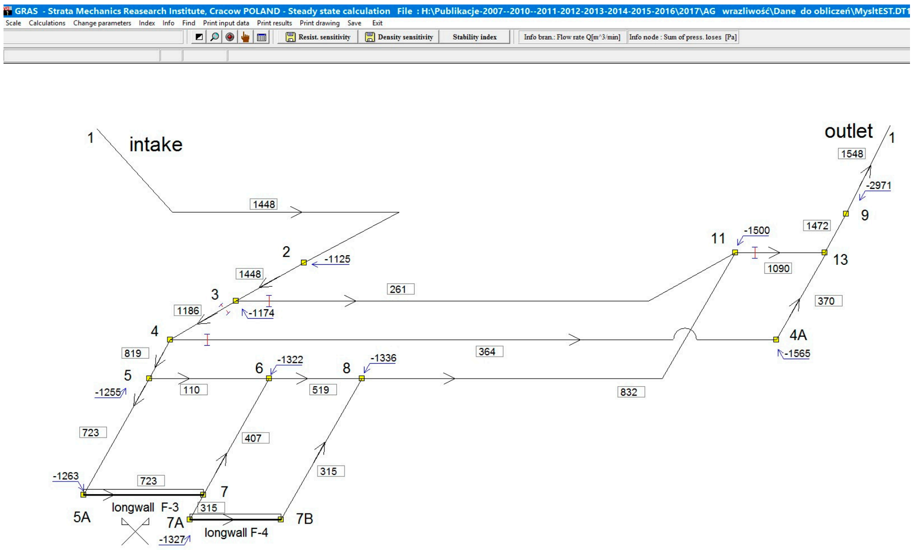

Fig. 1. *VentGraph* program window, GRAS module in rectangles – air flow volume stream, in nodes – potential (relative pressure) values.

Details of the network structures, workings of the area and parameters describing the flow in the workings region are listed in figure 2. [6], which is a copy of a *VentGraph* screen.

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Data format Edit Network Structure (p.I) Measurements Fans (p.IV) Pressure Find Print Save Calculator Exit

? W R Ro New branch New node Branch name

Branch No	Inlet node J1	Outlet node J2	Resis-tance kg/m^7	Average density kg/m^3	Initial flow m^3/s	Length of bran. m	Cross section m2	Z2-Z1 m	Inclin. deg.	Special W=Fan D=inflow
1	9	1	0.50000	1.160	25.6	360.0	25.0	360.00	90	W
2	1	2	1.93000	1.240	24.0	482.0	24.0	-482.23		
3	2	3	0.08560	1.240	24.0	1200.0	15.0	13.00	1	
4	3	4	0.08800	1.240	19.6	1000.0	12.0	-2.77	0	
5	4	5	0.25000	1.240	13.6	500.0	12.0	-18.00	-2	
6	5	5A	0.05133	1.220	11.9	600.0	14.8	-38.00	-4	
7	5A	7	0.35000	1.220	11.9	200.0	15.2	0.00	0	
8	7	7A	0.47800	1.210	5.2	50.0	12.6	-12.00	-14	
9	7A	7B	0.15000	1.210	5.2	200.0	15.7	0.00	0	
10	7B	8	0.18000	1.210	5.2	800.0	12.7	60.00	4	
11	8	11	0.85200	1.220	13.8	2000.0	13.7	10.00	0	
12	11	13	0.81000	1.230	18.0	2000.0	16.7	4.77	0	
13	13	9	2.00000	1.220	24.4	1000.0	16.8	105.23	6	
14	4	4A	9.67000	1.250	6.0	3500.0	10.7	0.00	0	
15	4A	13	5.09000	1.230	6.1	1600.0	10.7	6.77	0	
16	5	6	20.00000	1.220	1.8	200.0	10.6	0.00	0	
17	7	6	0.10300	1.230	6.7	600.0	12.8	38.00	4	
18	6	8	0.12200	1.220	8.6	200.0	11.7	10.00	3	
19	3	11	16.80000	1.250	4.3	1500.0	13.6	-0.77	0	

Fig.2. Details of the network structures.

The mine working area (subnetwork), as shown in figure 1, has been selected to exemplify calculations of the sensitivity indicator $\varepsilon_{i,j}$. In the GRAS steady flow calculation module of the *VentGraph* program, an additional 'Indicators' option is provided in the program menu. To make calculations after using this option, choose the 'Sensitivity indicators for selected branch' sub-option. When selected, and the i^{th} branch is indicated, a program window is opened, as shown in figure 3.

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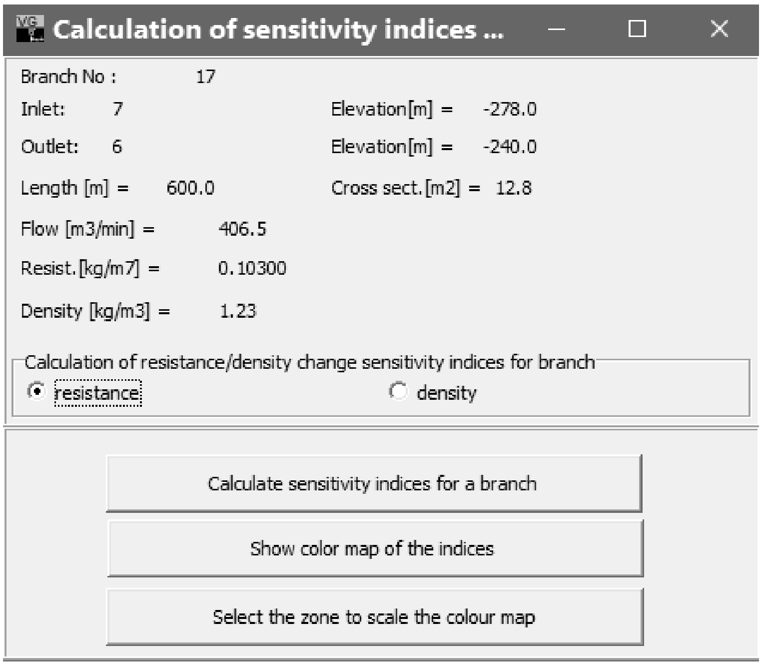

Fig. 3. Calculating sensitivity indicators for branch 17.

From the window shown in figure 3, sensitivity indicators may be calculated for branches of the selected area, due to the change of aerodynamic resistance of branch 17 or the change of density in that branch. Click on the active option button to make the selection.

With this function, sensitivity indicators shall be calculated for the network branches, due to the change in the chosen branch:

- resistance – left-hand button of the window;
- density – right-hand button of the window.

The matrix of sensitivity indicators created may be saved as a file with an extension 'name.wrR' or 'name.wRo', where the name is given by the user. This saving is enabled by the program option 'Sensitivity from R' and 'Sensitivity from Ro' available in the top bar of the *VentGraph* program.

The data are saved in a text file that can be read by MS Excel or Notepad. The sensitivity matrix $\varepsilon_{i,j}$ determined for a sample working network is presented below in Table 1 (for resistance changes) and in Table 2 (for density changes). Row numbers in the tables correspond to the numbers of branches in which the air volume stream is changed as a result of resistance change (Table 1) or air density (Table 2) in the branch with the table column name.

Table 1. Complete sensitivity matrix $\varepsilon_{i,j}$ of a network of mine workings for aerodynamic resistance changes.

Br.nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	-2,853	-2,597	-1,469	-1,101	-0,643	-0,553	-0,425	-0,042	-0,022	-0,023	-0,590	-1,164	-2,692	-0,031	-0,025	0,001	-0,063	-0,176	-0,011
2	-2,853	-2,597	-1,469	-1,101	-0,643	-0,553	-0,425	-0,042	-0,022	-0,023	-0,590	-1,164	-2,692	-0,031	-0,025	0,001	-0,063	-0,176	-0,011
3	-2,853	-2,597	-1,469	-1,101	-0,643	-0,553	-0,425	-0,042	-0,022	-0,023	-0,590	-1,164	-2,692	-0,031	-0,025	0,001	-0,063	-0,176	-0,011
4	-2,300	-2,107	-1,076	-2,670	-1,391	-0,885	-1,065	-0,061	-0,028	-0,042	-1,563	-0,763	-2,193	-0,057	-0,039	0,000	-0,221	-0,498	0,114
5	-1,621	-1,464	-0,942	-2,261	-1,830	-1,045	-1,437	-0,063	-0,028	-0,050	-2,138	-2,025	-1,520	0,133	0,145	-0,003	-0,318	-0,692	0,096
6	-1,379	-1,265	-0,643	-2,209	-1,843	-2,772	-3,308	-0,077	-0,042	-0,073	-1,951	-1,831	-1,316	0,119	0,133	0,044	-1,058	-0,551	0,087
7	-1,379	-1,265	-0,643	-2,209	-1,843	-2,772	-3,308	-0,077	-0,042	-0,073	-1,951	-1,831	-1,316	0,119	0,133	0,044	-1,058	-0,551	0,087
8	-0,423	-0,395	-0,125	-0,470	-0,389	-0,247	-0,592	-2,679	-2,528	-2,643	-0,557	-0,528	-0,411	0,038	0,041	0,004	4,236	6,992	0,025
9	-0,423	-0,395	-0,125	-0,470	-0,389	-0,247	-0,592	-2,679	-2,528	-2,643	-0,557	-0,528	-0,411	0,038	0,041	0,004	4,236	6,992	0,025
10	-0,423	-0,395	-0,125	-0,470	-0,389	-0,247	-0,592	-2,679	-2,528	-2,643	-0,557	-0,528	-0,411	0,038	0,041	0,004	4,236	6,992	0,025
11	-1,621	-1,464	-0,942	-2,261	-1,830	-1,045	-1,437	-0,063	-0,028	-0,050	-2,138	-2,025	-1,520	0,133	0,145	-0,003	-0,318	-0,692	0,096
12	-2,173	-1,954	-1,334	-0,693	-1,082	-0,713	-0,797	-0,044	-0,021	-0,031	-1,165	-2,426	-2,019	0,159	0,159	-0,002	-0,160	-0,370	-0,029
13	-2,853	-2,597	-1,469	-1,101	-0,643	-0,553	-0,425	-0,042	-0,022	-0,023	-0,590	-1,164	-2,692	-0,031	-0,025	0,001	-0,063	-0,176	-0,011
14	-0,679	-0,642	-0,134	-0,409	0,439	0,160	0,372	0,003	0,000	0,009	0,575	1,263	-0,673	-0,190	-0,184	0,003	0,097	0,194	0,017
15	-0,679	-0,642	-0,134	-0,409	0,439	0,160	0,372	0,003	0,000	0,009	0,575	1,263	-0,673	-0,190	-0,184	0,003	0,097	0,194	0,017
16	-0,242	-0,199	-0,298	-0,052	0,013	1,726	1,871	0,014	0,014	0,022	-0,187	-0,194	-0,204	0,014	0,012	-0,047	0,739	-0,140	0,009

17	-0,956	-0,870	-0,518	-1,739	-1,454	-2,525	-2,715	2,601	2,486	2,570	-1,394	-1,303	-0,905	0,081	0,093	0,040	-5,293	-7,543	0,062
18	-1,198	-1,069	-0,816	-1,791	-1,440	-0,798	-0,844	2,616	2,500	2,592	-1,581	-1,497	-1,109	0,094	0,104	-0,007	-4,554	-7,684	0,071
19	-0,552	-0,490	-0,393	1,569	0,748	0,332	0,640	0,019	0,007	0,019	0,973	-0,401	-0,499	0,026	0,015	0,001	0,158	0,322	-0,125

Table 2. Complete sensitivity matrix $\kappa_{i,j}$ of a network of mine workings for air density changes in branches.

Br. nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	2,570	8,222	0,321	0,196	0,232	0,053	0,245	0,025	0,007	0,007	0,830	1,511	8,952	0,574	0,290	-0,036	0,011	0,035	0,345
2	2,570	8,222	0,321	0,196	0,232	0,053	0,245	0,025	0,007	0,007	0,830	1,511	8,952	0,574	0,290	-0,036	0,011	0,035	0,345
3	2,570	8,222	0,321	0,196	0,232	0,053	0,245	0,025	0,007	0,007	0,830	1,511	8,952	0,574	0,290	-0,036	0,011	0,035	0,345
4	2,079	6,688	0,249	0,507	0,608	0,098	0,618	0,053	0,013	0,013	2,211	0,818	7,293	1,010	0,485	-0,024	0,039	0,100	-3,086
5	1,452	4,630	0,183	0,409	0,842	0,118	0,834	0,067	0,015	0,015	3,023	2,637	5,045	-2,001	-1,144	0,092	0,055	0,140	-2,613
6	1,247	4,020	0,148	0,368	0,772	0,270	1,928	0,092	0,022	0,022	2,754	2,315	4,382	-1,769	-1,019	-1,489	0,173	0,110	-2,335
7	1,247	4,020	0,148	0,368	0,772	0,270	1,928	0,092	0,022	0,022	2,754	2,315	4,382	-1,769	-1,019	-1,489	0,173	0,110	-2,335
8	0,387	1,259	0,043	0,105	0,221	0,038	0,346	2,220	0,678	0,798	0,789	0,723	1,374	-0,566	-0,324	-0,147	-0,723	-1,417	-0,712
9	0,387	1,259	0,043	0,105	0,221	0,038	0,346	2,220	0,678	0,798	0,789	0,723	1,374	-0,566	-0,324	-0,147	-0,723	-1,417	-0,712
10	0,387	1,259	0,043	0,105	0,221	0,038	0,346	2,220	0,678	0,798	0,789	0,723	1,374	-0,566	-0,324	-0,147	-0,723	-1,417	-0,712
11	1,452	4,630	0,183	0,409	0,842	0,118	0,834	0,067	0,015	0,015	3,023	2,637	5,045	-2,001	-1,144	0,092	0,055	0,140	-2,613
12	1,943	6,164	0,256	0,098	0,466	0,073	0,461	0,039	0,009	0,010	1,642	3,330	6,703	-2,437	-1,338	0,079	0,028	0,075	0,818
13	2,570	8,222	0,321	0,196	0,232	0,053	0,245	0,025	0,007	0,007	0,830	1,511	8,952	0,574	0,290	-0,036	0,011	0,035	0,345

14	0,628	2,058	0,066	0,097	-0,234	-0,020	-0,216	-0,013	-0,003	-0,003	-0,812	-1,819	2,248	3,011	1,628	-0,116	-0,017	-0,039	-0,473
15	0,628	2,058	0,066	0,097	-0,234	-0,020	-0,216	-0,013	-0,003	-0,003	-0,812	-1,819	2,248	3,011	1,628	-0,116	-0,017	-0,039	-0,473
16	0,204	0,610	0,035	0,041	0,070	-0,153	-1,094	-0,026	-0,007	-0,007	0,269	0,323	0,663	-0,232	-0,124	1,581	-0,118	0,029	-0,278
17	0,860	2,761	0,105	0,263	0,551	0,233	1,582	-2,128	-0,655	-0,775	1,966	1,591	3,008	-1,203	-0,695	-1,343	0,897	1,527	-1,623
18	1,064	3,370	0,141	0,304	0,621	0,080	0,488	-2,153	-0,662	-0,782	2,235	1,914	3,671	-1,435	-0,819	0,239	0,778	1,557	-1,901
19	0,491	1,534	0,073	-0,311	-0,376	-0,045	-0,372	-0,028	-0,006	-0,006	-1,381	0,693	1,658	-0,436	-0,195	-0,013	-0,028	-0,065	3,431

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An important part of working with a computer program is to adopt a 'useful and friendly' way of presenting the results of any determined sensitivity matrix, so that the information presented will be useful in practice, particularly regarding air flow adjustment in a complex network of workings. Therefore, a graphic presentation of the results directly in an isometric diagram of the network of workings was proposed. Existing experience proves that, from a practical point of view, such a presentation of results provides useful data for a ventilation engineer.

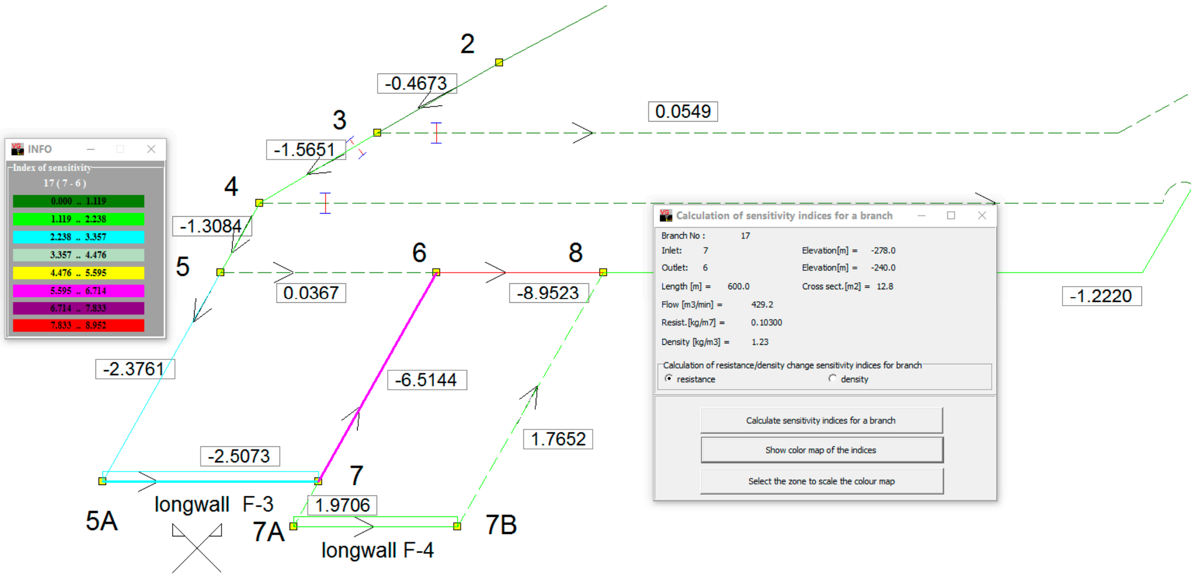

Fig. 4. Ventilation network area with presentation of a sensitivity indicator for resistance changes of a branch in the adopted color scale.

Because of the size of the sensitivity matrix $\varepsilon_{i,j}$ and the availability of only up to eight colors in the *VentGraph* program, it was proposed to show only the results for the given area of workings selected in the diagram. After choosing the option in the lower window shown in figure 3, **'Select network area to display indicators in color scale'**, click the left mouse button and, keeping it pressed, drag the mouse to expand the white rectangular contours. Release the mouse button to finish selection of the network area to display. Then, place the mouse cursor in the white rectangle area (cursor form changes) and click the mouse to display the sensitivity indicator in the selected color scale.

After their values are calculated by the program, the network branches shall be displayed in colors from the color scale presented in a separate panel. The borders of the colors scale are calculated from the indicator module, starting from 0, to the maximum absolute value of the indicator (divided equally into 8 colors). Branches for which the indicator value is positive are represented with dashed lines, and the negative ones with continuous lines. The branch for which the indicators are calculated is additionally marked with a double line in the relevant color.

Figure 4 shows, on the basis of a test example, the result of the calculation of sensitivity indicators $\varepsilon_{j=1...19,i=17}$ for the change of branch resistance no. 17 (inlet-node 7 – outlet-node 6); this branch is marked with two bold lines and, in this case, in red color.

Figure 5 shows the area of longwall N-15, for which the sensitivity indicators determined are presented graphically, for density change in working no. 377, i.e. longwall N-15. The sample ventilation network of mine 'K' is created from 498 workings (branches). For the 'K' mine, the module of sensitivity indicator value, for the changes of aerodynamic resistance, falls within the range of 0 to 3134, and for the sensitivity factor, for the density changes, from 0 to 6.8. Interpretation of the sensitivity indicators is given in par. 3.2 and 3.4.

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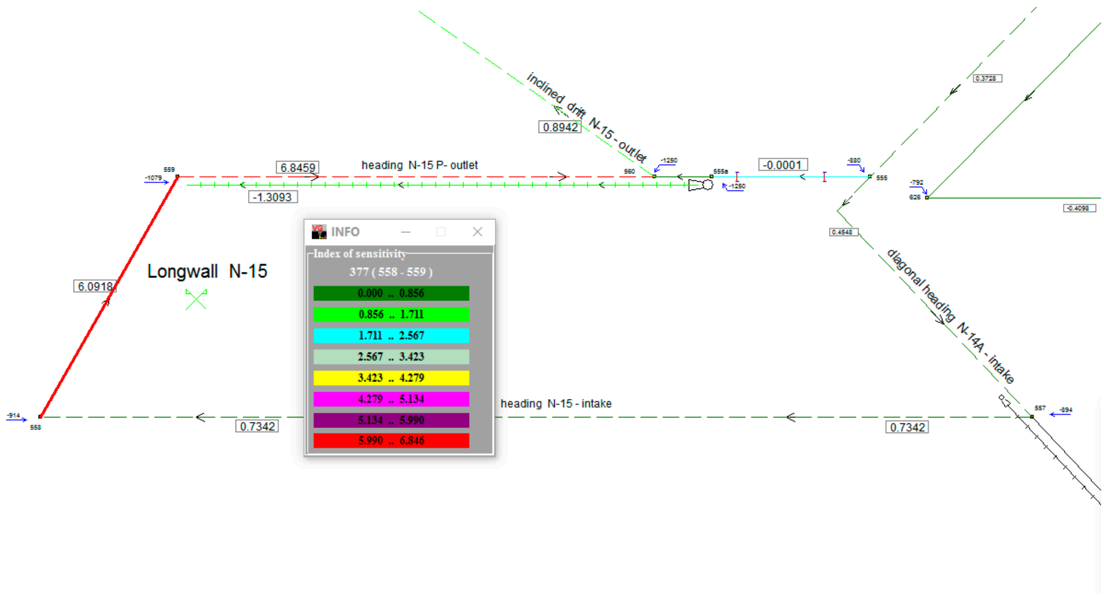

Fig. 5. Ventilation network area with presentation of a sensitivity indicator **for density changes in the adopted color scale.**

5. Summary

This paper presents new options for determining the sensitivity of local subnetwork flows to the change of air flow directions. The method chosen to meet the objective involves an extended possibility to predict the process of ventilation, air distribution and, in the case of underground fire, also the spread of fire gasses. Widespread use of computer programs, including the *VentGraph* system, facilitates assessment by mine ventilation services of the stability of ventilation systems in exploitation areas and determination of the sensitivity of local area flows to changes of air flow directions.

While analyzing air distributions for the exploitation below the level of access, application of current numerical models for calculations of the distributions results in tangible benefits, such as the evaluation of the safety or risk levels for such exploitation. Application of the *VentGraph* computer program, and particularly the module *POŻAR (fire)* [8], together with the newly developed options enables a comprehensive analysis of distribution for the real risks present in a specific case during exploitation below the level of access. The analyses performed and examples presented support the following statements:

- For the evaluation of air flow in workings below the level of access, a new approach to the problem has been proposed and formulae have been developed to determine the sensitivity of local area air flows due to the change (decrease) of air density. Determination of the sensitivity of the local area air flows presents the degree of dependency of the air volume stream in a given working on the changes of resistance or density in other workings included in the network. Interpretations of the sensitivity indicator are presented in par. 2.3 and 2.4.
- Since it is difficult to predict the distribution of fire gasses in the case of an underground fire, for newly designed working areas below the level of access, it is recommended to investigate the possibility of changes of the volume (mass) of air flow (fire gasses) during a fire, using the POŻAR (fire) module of the *VentGraph* program. Currently, this is the only tool enabling the prediction of variation in the duration of a fire and its impact on the distribution pattern of air and fire gasses. The results obtained confirm the usefulness of the algorithms developed for the analysis and assessment of changes in the direction and the volume stream of air flowing in the ventilation system of an underground mine.

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