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COSTS REDUCTION OF MAIN FANS OPERATION ACCORDING TO SAFETY VENTILATION IN MINES – A CASE STUDY

REDUKCJA KOSZTÓW PRACY WENTYLATORÓW GŁÓWNEGO PRZEWIETRZANIA PRZY ZACHOWANIU BEZPIECZNEJ WENTYLACJI – STUDIUM PRZYPADKÓW

Considering the various hazards present in an underground mine, safe ventilation entails maintaining a certain airflow rate in the mining workings. The air velocity, airflow rate and air composition must be regulated in a ventilation network by operation of the main fans. On the other hand, ventilation costs must be minimized. Thus, the optimal solution is when the requisite safety features are fulfilled and the power output of the fans is at a minimal yet sufficient rate.

In real-world mines, it is common to have airstreams interlinking subnets of the main fans. The current restructuring of the mining sector commonly involves the connection of different mines, which leads to an increase in the number of such cases. This article presents the results of research into ventilation networks containing these kind of airstreams and introduces a new method for reducing ventilation costs.

The method is based on an algorithm which allows the determination of the resistance of a stopping, the head of the fans and the air quantity for which air distribution is optimal. As a result, the total power output of the fans is at the lowest level that yields a reduction in ventilation costs. The method was applied for two theoretical examples and a practical one which was taken from a real ventilation network. In the first example, fan power output was reduced by 17.252 kW, which gave an annual reduction of 188.909 MWh, and an annual electricity cost reduction of €27014. Therefore, optimization enabled a saving of approximately 14% of the costs. In the second example, power output was reduced by 106.152 kW, which produced an annual reduction of 1162.364 MWh, and an annual electricity cost reduction of €166218. In this case, optimization allowed a reduction in costs of approximately 40%. Considering both examples, the cost reductions did not affect the safe airflow rate. For the real-world mine, the annual savings were 2343 MWh, which corresponds to approximately €335000.

Keywords: mine ventilation network, forced airflow, dependent air streams, ventilation costs, airflow optimization, safe mining ventilation

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Ze względu na zagrożenia występujące w podziemnej kopalni bezpieczna wentylacja powinna zapewniać dostarczenie właściwego wydatku objętościowego powietrza do wyrobisk górniczych. Wentylatory głównego przewietrzania powinny zapewnić w wyrobiskach bezpieczną prędkość powietrza oraz jego skład chemiczny . Jednocześnie ze względów ekonomicznych istotna jest minimalizacja jej kosztów. Celem więc jest znalezienie optymalnego rozpływu powietrza uwzględniającego bezpieczeństwo górników i minimalizującego zużycie energii przez wentylatory.

W istniejących kopalniach występują prądy powietrza łączące podsieci wentylatorów głównego przewietrzania. Aktualnie prowadzona restrukturyzacja górnictwa polegająca także na łączeniu kopalń przyczynia się do zwiększenia liczby takich prądów. W artykule zaprezentowano wyniki badań nad sieciami wentylacyjnymi zawierającymi wspomniane prądy powietrza. Przedstawiono nową metodę pozwalającą na obniżenie kosztów wentylacji.

Przedstawiony w pracy algorytm pozwala na wyznaczenie wartości oporu tamy regulacyjnej oraz spiętrzenia i wydajności wentylatorów, przy których rozpływ powietrza jest optymalny. Uzyskiwana przy nim wartość sumarycznej mocy użytecznej wentylatorów jest najniższa, co przyczynia się do obniżenia kosztów związanych z wentylacją.

W artykule przedstawiono wyniki optymalizacji przeprowadzonej według nowej metody dla dwóch przykładów teoretycznych oraz dla rzeczywistej sieci wentylacyjnej kopalni. W pierwszym przykładzie uzyskano zmniejszenie mocy użytecznej wentylatorów o 17 252 W, rocznego zużycia energii 188 909 kWh, rocznych kosztów za energię elektryczna 113 345 zł. Oszczędności wyniosły 14% względem stanu przed optymalizacja. Dla drugiego przykładu uzyskano odpowiednio spadki: mocy o 106 152 W, rocznego zużycia energii o 1 162 364 kWh, rocznych kosztów 697 418 zł. W tym przykładzie zastosowanie metody pozwoliłoby uzyskać oszczędności na poziomie 40%. Dla rzeczywistej kopalni roczne oszczędności wyniosły 2 343 MWh, co odpowiada w przybliżeniu 335 000 Euro.

Słowa kluczowe: kopalniana sieć wentylacyjna, rozpływ wymuszony powietrza, prądy zależne, koszty wentylacji, optymalizacja rozpływu powietrza, bezpieczna wentylacja kopalni

1. Introduction

Ventilation is crucial for workers' safety in underground mines (Madeja-Strumińska & Strumiński, 2004a; 2004b). This is an important element for protection against the following: methane hazards, fire hazards, dust hazards and thermal hazards (Szlązak et al., 2008, 2013; Szlązak & Kubaczka, 2012; Zhong et al., 2003; Knechtel, 2011; Liu et al., 2017). Prevention is based on assuring the required level of airflow rate, which is determined on the basis of the regulations (Wacławik, 2010), standards and forecasts of hazards for working areas, headings and chambers (PN-G-05204, 1999; Regulation, 2002a; Regulation, 2002b). For instance, in Polish underground mines the air velocity at longwall faces must be in a range between 0.3 m/s and 5.0 m/s. It is sufficiently high to dilute methane and other gases and also to mitigate thermal hazards. On the other hand, it is sufficiently low to protect against fire hazards in goafs and against dust explosions. For example, according to proper regulations (Regulation, 2002 a, b), the airflow rate must be sufficient to keep the methane concentration below $2.0\%_{vol}$ in return airstream at the outlet of a longwall face. This is achieved by operation of the main fans.

At least 25% (Jeswiet et al., 2015; Jeswiet & Szekeres, 2016) of electrical energy consumed by mining is used for ventilation purposes (Turek, 2013). Mielli and Bongiovanni (2013) stated that approximately 15-40% of the operating costs of a mine are associated with energy consumption. According to (Crittenden, 2016; Sui et al., 2011; Chatterjee et al., 2015), cost reduction can be achieved by: optimization of ventilation systems, maintaining sufficient amounts of air in the mine workings and improvement of fan operation.

Regulation of a ventilation network is tightly bound to airflow optimization in a mine (Madeja-Strumińska & Strumiński, 2004a, 2004b; Sałustowicz, 1930). There is a set of input data: the structure of a network, air resistance of the branches, and assumed "a priori" air quantity in selected branches. The unknown values are: appropriate operating location of a fan (including fan head and air quantity) and the location and setting of stoppings or auxiliary fans that are located underground. If air density is not taken to be constant, additional processes such as heat and mass exchange should be included.

The dependent air stream is defined as the air flowing through a branch which links two intake air streams or two return air streams. For example, according to Sułkowski and Wilson (Sułkowski, 1971; Wilson, 2012) the dependent stream can be determined through analysis of the chains of the branches in the network. Therefore, mine ventilation networks can be divided into (Kolarczyk 1993):

– those without dependent air streams,
– those with dependent air streams.

Networks with dependent air streams can be additionally subdivided into:

– networks with dependent air streams in the area of intake and/or return airstream but without cross-system air streams (a cross-system air stream is defined as linking subnetworks of main fans),
– networks with cross-system airflows.

For example, networks with cross-system air streams are common in Polish underground mining. This is a result of intensive transformation and restructuring of the mining sector and the priority given to safety features and cost reduction.

The results presented in this article show that there is a method to decrease the costs of mine ventilation while also maintaining safety at the same level. The examples provided are related to methane hazards. The examples were elaborated for mines subsequent to their connection, where their networks have return air streams which link two subnetworks of main fans.

The method presented is a novel one, in that it is not currently applied in mines.

2. Forced airflow in a network with cross-system airflows

In financial terms, the most appropriate air distribution in a network occurs when the power output of the fans is the lowest (Sui et al., 2011; Chatterjee et al., 2015). It requires selection of the stoppings, fan head and air quantity. Fig. 1 presents a three-dimensional output schematic of a mine. There are two main fans: $W1$ and $W2$. Operating area A is between nodes 3 and 4 and operating area B is between nodes 3 and 5. Operating areas are supplied with air through branches 1-2 and 2-3. Then, in node 3, the air is divided into particular areas. Return air flows to fans $W1$ and $W2$. The dependent air stream (branch 4-5) is a specific feature of this network. It links the two subnets of fans $W1$ and $W2$ and allows the distribution of return air between them. This distribution can be achieved by setting the stoppings in selected branches.

Based on Fig. 1, a canonical diagram was created (Fig. 2). Branches 1-2 and 2-3 are linked in series; therefore, in the canonical diagram they are linked as one branch assigned as "0". The branches were labeled in a predetermined manner – numbers and letters with a line above. The letters refer to the working areas (A and B), the numbers correspond to the rest of the branches. Dotted lines drawn in the diagram denote branches without air resistance (4, 5 and 6) representing the atmosphere. Node 8 is located in the atmosphere. Branch 1 links two subnetworks of fans,

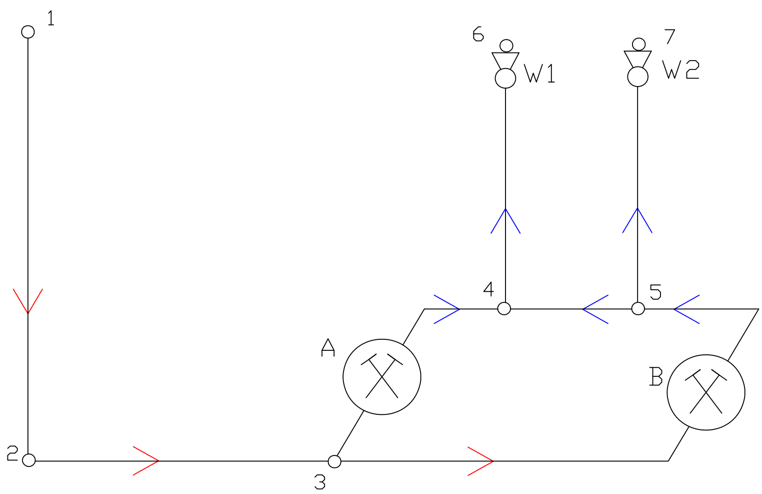

Fig. 1. Three-dimensional output schematic of mine “A” (*own source*)

*W*1 and *W*2. The stopping *TR* is in branch *A*. Even a small change in the air resistance of a stopping results in a variation of airflow rate in the branches (Dziurzyński et al., 2017). The effect of the application of this stopping is presented later in the text (sections 3 and 4). Fig. 2 includes 7 nodes and 9 branches. Therefore, according to, for instance, (Wilson, 2012), the cyclomatic number of this network is 3. This means that it is possible to write 3 cyclic equations according to Kirchhoff’s Second Law.

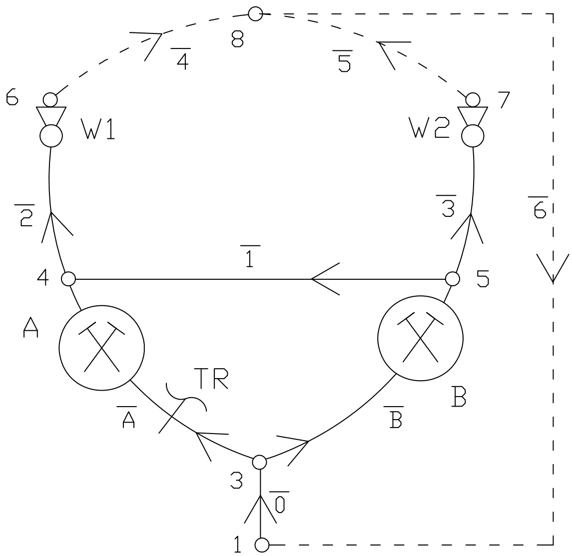

Fig. 2. The canonical diagram of mine “A” (*own source*)

As has been mentioned previously, several air quantities are assumed as a given. In this case, these are V_a in working section A and V_b in working section B. Air quantities must ensure safe working conditions in the face of natural hazards (e.g. methane hazards). The air resistances of all the branches are known, they are as follows: R_0, R_1, R_2, R_3, R_4, R_5, R_6, R_A, R_B. The resistances of $\overline{4}$, $\overline{5}$ and $\overline{6}$ are zero. Thus, the unknown values are: air quantity in $\overline{0}$, $\overline{1}$, $\overline{2}$, $\overline{3}$, $\overline{4}$, $\overline{5}$ and $\overline{6}$, (V_0, V_1, V_2, V_3, V_4, V_5, V_6), fan head of $W1$ and $W2$ (Δp_{W1} and Δp_{W2}) and resistance of the stopping (R_{TR}). Therefore, there are 10 unknown values; however, based on the principal balance equations for a network, there are only 9 possible equations to formulate (including 6 equations for the nodes and 3 equations for the cycles). Therefore, the number of unknowns is higher than the number of independent equations. This leads to the conclusion that there are countless solutions for forced airflow in this case. Particular solutions vary in terms of: air quantities in branches $\overline{1}$, $\overline{2}$, $\overline{3}$, $\overline{4}$ and $\overline{5}$ (including airflow through $W1$ and $W2$), resistance of the stopping (R_{TR}) and fan heads of $W1$ and $W2$. Thus, every solution gives different power outputs for each fan and total power output by both.

3. A new method for the determination of optimal air distribution in a network with a cross-system air stream

As was stated for the example shown in Fig. 2, there are 10 unknown values and 9 independent equations. These can be solved by the "a priori" assumption of some value, for example, when R_{TR} is assumed the following can be determined:

- air quantity in branch 1 – based on Kirchhoff's Second Law for a cycle which consists of branches A, B and 1
- air quantity in branches $\overline{2}$ and $\overline{3}$ (and in $\overline{4}$, $\overline{5}$, $\overline{6}$) – based on Kirchhoff's First Law for nodes 4, 5, 6, 7 and 8
- fan heads Δp_{W1} and Δp_{W2} – based on Kirchhoff's Second Law for external cycles (with an "atmosphere" branch)
- power output of $W1$ and $W2$ as a product of their air quantity and heads.

Theoretically, the resistance of the stopping can be assumed in any way, thus there are an infinite number of solutions. Therefore, the mentioned above parameters vary according to the solution.

Including Kirchhoff's First Law for nodes 4 and 5 (Fig. 2), the following equations can be written:

$$V_2 = V_A + V_1 \tag{1a}$$

$$V_3 = V_B - V_1 \tag{1b}$$

where: V_i — air quantity.

Air quantity in branch $\overline{0}$ equals the sum of air quantities in branches A and B, which are already known.

Fan heads for $W1$ and $W2$ can be determined with the following equations:

- fan $W1$

$$\Delta p_{W1} = R_0 \cdot (V_0)^2 + R_B \cdot (V_B)^2 + R_1 \cdot V_1 \cdot |V_1| + R_2 \cdot (V_2)^2 \tag{2a}$$

– fan $W2$

$$\Delta p_{W2} = R_0 \cdot (V_0)^2 + R_B \cdot (V_B)^2 + R_3 \cdot (V_3)^2 \tag{2b}$$

where:

R_i — aerodynamic resistance,

Δp_W — fan head.

The absolute value of V_1 in Eq. (2a) indicates the allowable change of airflow direction in branch $\overline{1}$ (according to the direction given in Fig. 2). Airflow directions in branches $\overline{2}$ and $\overline{3}$ are determined unambiguously (according to the function of the excavations, e.g. intake shafts – see Fig. 1).

Power output of the fans $W1$ and $W2$ is expressed by:

– fan $W1$

$$N_{uW1} = \Delta p_{W1} \cdot V_2 = \begin{pmatrix} R_0 \cdot (V_0)^2 + R_B \cdot (V_B)^2 + \\ + R_1 \cdot V_1 \cdot |V_1| + R_2 \cdot (V_A + V_1)^2 \end{pmatrix} \cdot (V_A + V_1) \tag{3a}$$

– fan $W2$

$$N_{uW2} = \Delta p_{W2} \cdot V_3 = \left(R_0 \cdot (V_0)^2 + R_B \cdot (V_B)^2 + R_3 \cdot (V_B - V_1)^2\right) \cdot (V_B - V_1) \tag{3b}$$

One should note that functions (3a) and (3b) are a function of a single independent variable (air quantity V_1). The rest of the parameters are known. Thus, a function which determines total fan power output $W1$ and $W2$ ($N_{u\,W1,W2}$) also depends only on one and the same variable, V_1. Therefore, the total fan power output of $W1$ and $W2$ as a function of V_1 is given as Eq. (4):

$$\begin{aligned} N_{u\,W1,W2} &= (R_2 - R_3) \cdot (V_1)^3 + (3 \cdot R_2 \cdot V_A + 3 \cdot R_3 \cdot V_B) \cdot (V_1)^2 + \\ &+ \left(3 \cdot R_2 \cdot (V_A)^2 - 3 \cdot R_3 \cdot (V_B)^2\right) \cdot (V_1) + R_1 \cdot (V_1)^2 \cdot |V_1| + R_1 \cdot V_A \cdot V_1 \cdot |V_1| + \\ &+ R_B \cdot (V_B)^2 \cdot V_A + R_2 (V_A)^3 + R_B \cdot (V_B)^3 + R_3 \cdot (V_B)^3 + R_0 \cdot (V_A + V_B)^3 \end{aligned} \tag{4}$$

According to Eq. (4), total fan power output depends on air quantity cubed in the branches and this corresponds to ventilation network theories (McPherson, 2012).

To simplify the derivation further, additional coefficients are introduced (a, b, c and d). These can be determined using Eqs. (5a)-(5d).

$$a = R_2 - R_3 \tag{5a}$$

$$b = 3 \cdot R_2 \cdot V_A + 3 \cdot R_3 \cdot V_B \tag{5b}$$

$$c = 3 \cdot R_2 \cdot (V_A)^2 - 3 \cdot R_3 \cdot (V_B)^2 \tag{5c}$$

$$d = R_B \cdot (V_B)^2 \cdot V_A + R_2 (V_A)^3 + R_B \cdot (V_B)^3 + R_3 \cdot (V_B)^3 + R_0 \cdot (V_A + V_B)^3 \tag{5d}$$

Then, total power output can be determined by application of Eq. (6):

$$N_{u\,W1,W2} = a \cdot (V_1)^3 + b \cdot (V_1)^2 + c \cdot (V_1) + d + R_1 \cdot (V_1)^2 \cdot |V_1| + R_1 \cdot V_A \cdot V_1 \cdot |V_1| \tag{6}$$

Considering the previously mentioned function of return shafts and the necessary direction of the airflow, airstream V_1 must be within the following range Eq. (6a):

$$V_1 \in \left[-V_A, V_B\right] \tag{6a}$$

Negative values of V_1 would indicate airflow from node 4 to node 5. A value of V_1 higher than V_B would indicate reversal of airflow in branch 3 (Fig. 2).

When considering the optimization of air distribution in a network by minimization of total power output, it is useful to apply the first and the second order derivatives of the function given as Eq. (6). These derivatives can be determined using Eqs. (7) and (8):

$$\left(N_{u\,W1,W2}\right)' = 3a \cdot (V_1)^2 + 2b \cdot V_1 + c + \frac{2 \cdot R_1 \cdot V_A \cdot (V_1)^2}{|V_1|} + \frac{3 \cdot R_1 \cdot (V_1)^3}{|V_1|} \tag{7}$$

$$\left(N_{u\,W1,W2}\right)'' = 6a \cdot V_1 + 2b + \frac{2 \cdot R_1 \cdot V_A \cdot (V_1)^3}{|V_1|^3} + \frac{6 \cdot R_1 \cdot (V_1)^4}{|V_1|^3} \tag{8}$$

When Eq. (7) is compared to zero and is then solved, it allows determination of the optimal V_1. For the determined V_1, it is necessary to compute the derivative of the second order of the power output (8). If the result is positive, this indicates that there is a minimum of the function (4) for the prior V_1. When considering the discontinuity of function (7) for $V_1 = 0$, it is necessary to determine total power output based on (4) and (5d). Then, power output equals d (5d).

After determination of air quantity in branch 1 (Fig. 2), the following steps are necessary:

- to determine air quantities in the rest of the branches – based on Kirchhoff's First Law for ventilation networks (1a) and (1b)
- to determine the required fan heads for $W1$ and $W2$ – on the basis of Kirchhoff's Second Law for ventilation networks (2a) and (2b)
- to determine the total power output of fans $W1$ and $W2$ – on the basis of Eq. (4)
- to determine the resistance R_{TR} of the stopping – on the basis of Kirchhoff's Second Law for a cycle consisting of branches A, B, 1.

It should be noted that this method allows air quantities in the branches A and B to be kept at the same level, which corresponds to the hazards level.

4. Case studies

Given the minimization of total energy output of the fans, optimal air distribution for the network given in Fig. 2 was computed. The new algorithm was applied.

Safe air quantity was computed on the base of equation (9):

$$V = c\frac{100 \cdot V_{\mathrm{CH_4}}}{k_{\max} - k} \tag{9}$$

where:

V — necessary air quantity (airflow rate), m^3/s,

$k_{\max}$ — maximal methane concentration in return air at the outlet of a longwall face, 2%$_{vol}$,
k — methane concentration in intake air at the inlet to a longwall face, %$_{vol}$,
V_{CH_4} — absolute methane content, m^3/s,
c — coefficient of irregular methane emissions to a longwall face, for the most cases 1.5.

Example 1

Assumptions which are necessary for determination of the safe airflow rate in branches *A* and *B*:

- Branch A
  $c = 1.5$; $V_{CH_4} = 0.15$ m^3/s; $k_{\max} = 2\%_{vol}$; $k = 0.5\%_{vol}$;
- Branch B
  $c = 1.5$; $V_{CH_4} = 0.48$ m^3/s; $k_{\max} = 2\%_{vol}$; $k = 0.2\%_{vol}$.

Computed airflow rates (on the basis of equation 9) are presented in Table 1.

A mine ventilation network (Fig. 2) consisting of the following branches (Table 1).

TABLE 1

The characteristics of the branches – example 1

Number of the branch	Branch resistance kg/m^7	Safe air quantity m^3/s	Remarks
0	0.3	—	—
1	2.0	—	—
2	0.3	—	—
3	1.0	—	—
4	0	—	atmosphere
5	0	—	atmosphere
6	0	—	atmosphere
A	1.5	15	working area
B	0.2	40	working area

The state before optimization

If there is no stopping in branch *A* ($R_{TR} = 0$), V_1 can be determined by applying Kirchhoff's Second Law for the cycle that includes 1, *A* and *B*. In this case, $V_1 = 2.96$ m^3/s. The operating point includes the following values: air quantities which are produced by fans $W1 = 17.96$ m^3/s, $W2 = 37.04$ m^3/s and fan heads $\Delta p_{W1} = 1341.8$ Pa, $\Delta p_{W2} = 2599.5$ Pa. Therefore, total fan power output is 120 384 W.

Optimization

To find the optimal solution, the following steps were undertaken. Coefficients a, b, c and d were determined on the basis of equations (5a)-(5d). These are as follows: $a = -0.7$, $b = 133.5$, $c = -4\,597.5$, and $d = 132\,525$. Then, Eq. (10) is applied. Total fan power output as the function of V_1 (6) is written as (10):

$$N_{u\,W1,W2} = -0{,}7\cdot(V_1)^3 + 133{,}5\cdot(V_1)^2 - 4597{,}5\cdot(V_1) + \\ + 132525 + 2\cdot(V_1)^2\cdot|V_1| + 30\cdot V_1\cdot|V_1| \tag{10}$$

Figure 3 presents the function given by equation (10). It should be emphasized that the lack of airflow in branch 1 does not signify optimal air distribution. In this case, the total power output of the fans is 132 525 W and this is higher than minimal (Fig. 3).

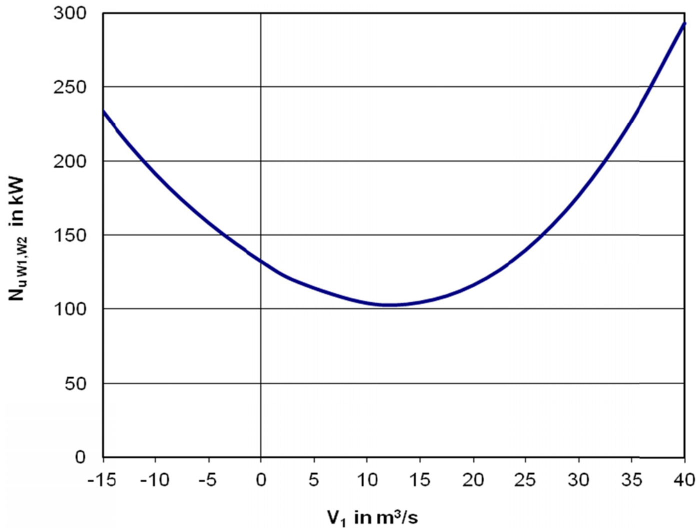

Fig. 3. Total fan power output of the fans $W1$ and $W2$ as a function of V_1 (airflow in branch $\overline{1}$) – example 1 (*own source*)

The derivative of the first order (7) of this function (10) V_1 is:

$$\left(N_{u\,W1,W2}\right)' = -2{,}1\cdot(V_1)^2 + 267\cdot V_1 - 4597{,}5 + \frac{60\cdot(V_1)^2}{|V_1|} + \frac{6\cdot(V_1)^3}{|V_1|} \tag{11}$$

If the function (11) is compared to zero and is solved, then the minimum value of the function (10) can be found. Then, $V_1 = 12.27\ \mathrm{m^3/s}$. The derivative of the second order (8) for the total power output of the fans can be determined on the basis of:

$$\left(N_{u\,W1,W2}\right)'' = -4{,}2\cdot V_1 + 267 + \frac{60\cdot(V_1)^3}{|V_1|^3} + \frac{12\cdot(V_1)^4}{|V_1|^3} \tag{12}$$

and for $V_1 = 12.27$ this equals 422.7. A positive result indicates that there is a minimum of the function at this point.

Following this, the airflow in branches $\overline{2}$ and $\overline{3}$ was determined on the basis of (1a) and (1b). V in $\overline{2} = 27.27\ \mathrm{m^3/s}$, and V in $\overline{3} = 27.73\ \mathrm{m^3/s}$. The fan heads for $W1$ and $W2$ were determined using (2a) and (2b). The solution is: $\Delta p_{W1} = 1751.7$ Pa, and $\Delta p_{W2} = 1996.5$ Pa. Thus, the total power output of the fans is 103 132 W and this is lower than the value obtained previously, when no stopping was present (i.e. 120 384 W).

To achieve this solution, it is necessary to construct a stopping with R_{TR} = 1.26 kg/m^7. This allows 17 252 W to be saved (a decrease in fan total output of 14%) and for the airflow in branches $\overline{A}$ and $\overline{B}$ to be maintained at the rates of 15 m^3/s and 40 m^3/s, respectively. To introduce calculations of the costs, one should bear in mind that the fans are operating continuously in a mine. Assuming that fan efficiency is 80%, and comparing the state before and after optimization, the saving is 188 909 kWh/year. Assuming that the price of 1 kWh is €0.143, the method outlined above gives an annual saving of €27 014 (Fig. 4).

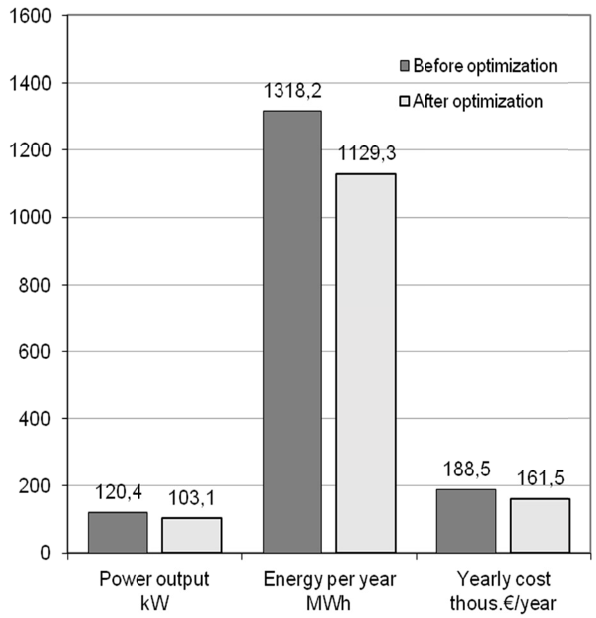

Fig. 4. Comparison of selected fan parameters before and after optimization – example 1 (*own source*)

Example 2

Assumptions which are necessary for determination of the safe airflow rate in branches *A* and *B*:

- Branch *A*

  c =1.5; V_{CH_4} = 0.25 m^3/s; $k_{\max}$ = 2%$_{vol}$; k = 0.5%$_{vol}$;

- Branch *B*

  c =1.5; V_{CH_4} = 0.34 m^3/s; $k_{\max}$ = 2%$_{vol}$; k = 0.3%$_{vol}$.

Computed airflow rates (on the basis of equation 9) are presented in Table 2.

A mine ventilation network (Fig. 2) consisting of the following branches (Table 2).

TABLE 2

The characteristics of the branches – example 2

Number of the branch	Branch resistance kg/m^7	Safe air quantity m^3/s	Remarks
0	0.4	—	—
1	1.0	—	—
2	1.2	—	—
3	1.5	—	—
4	0	—	atmosphere
5	0	—	atmosphere
6	0	—	atmosphere
A	0.5	25	working area
B	0.7	30	working area

The state before optimization

If there is no stopping (Fig. 2, R_{TR} = 0), the airflow in branch $\overline{1}$ is $V_1 = -17.82$ m^3/s. A negative result means that the airflow in branch $\overline{1}$ is from node 4 to node 5. The air quantity of $W1$ is 7.18 m^3/s, and that of $W2$ is 47.82 m^3/s. The required fan heads are Δp_{W1} = 1584.4 Pa, Δp_{W2} = 5270.1 Pa. Thus, total fan power output is 263 393 W.

Optimization

According to Eqs. (5a)-(5d), the coefficients a, b, c and d are: $a = -0.3$, $b = 225$, $c = -1800$, and d = 160 450. Including (6), this represents:

$$N_{u\,W1,W2} = -0{,}3 \cdot (V_1)^3 + 225 \cdot (V_1)^2 - 1800 \cdot (V_1) + \\ + 160450 + 1 \cdot (V_1)^2 \cdot |V_1| + 25 \cdot V_1 \cdot |V_1| \tag{13}$$

Fig. 5 shows function (13).

The derivative of the first order of Eq. (13) is Eq. (14):

$$\left(N_{u\,W1,W2}\right)' = -0{,}9 \cdot (V_1)^2 + 450 \cdot V_1 - 1800 + \frac{50 \cdot (V_1)^2}{|V_1|} + \frac{3 \cdot (V_1)^3}{|V_1|} \tag{14}$$

Function (14) reaches zero when $V_1 = 3.55$ m^3/s. The derivative of the second order is given as (15):

$$\left(N_{u\,W1,W2}\right)'' = -1{,}8 \cdot V_1 + 450 + \frac{50 \cdot (V_1)^3}{|V_1|^3} + \frac{6 \cdot (V_1)^4}{|V_1|^3} \tag{15}$$

For V_1 = 3.55, this equals 514.91, which indicates that there is a minimum of the function (13) for this airflow. Introducing Eq. (1a) and Eq. (1b), the airflow in branches $\overline{2}$ and $\overline{3}$ is determined as: $V_2 = 28.55$ m^3/s, $V_3 = 26.45$ m^3/s. The required fan heads (on the basis of 2a and 2b) are $\Delta p_{W1} = 2830.7$ Pa, $\Delta p_{W2} = 2889.4$ Pa. Thus, total fan power output is 157 241 W and this is lower than that prior to the optimization (without a stopping, it was 263 393 W). To obtain optimal air distribution in the network, a stopping with $R_{TR} = 0.53$ kg/m^7 must be constructed in branch $\overline{A}$.

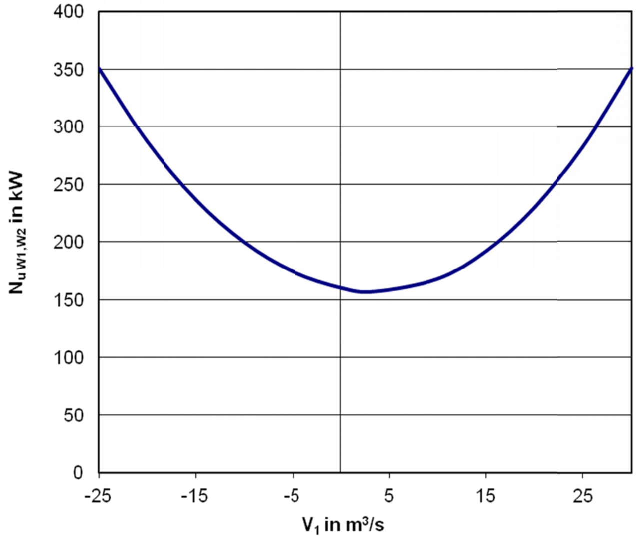

Fig. 5. Total fan power output of fans $W1$ and $W2$ as a function of V_1 (airflow in branch $\overline{1}$) – example 2 (*own source*)

This example shows that optimization of air distribution by the new method can reduce total fan output by 106 152 W (approximately 40%) compared to the state where there is no stopping (Fig. 6). Assuming a fan efficiency of 80%, the saving is 1 162 364 kWh/year. If 1 kWh costs 0.143 €/kWh, this gives an annual saving of €166 218.

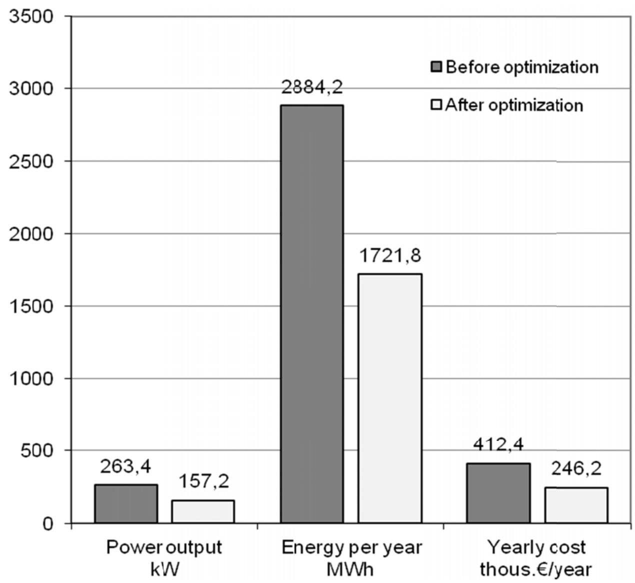

Fig. 6. Comparison of selected fan parameters before and after optimization – example 2 (*own source*)

5. Application of the method for complex ventilation networks

When there are single branches linking subnetworks of the main fans, the method may also be used for complex ventilation networks. To obtain the required input data it is useful to apply one of the existing computer programs (Dziurzyński & Kruczkowski, 2007; Dziurzyński & Krawczyk, 2012; Dziurzyński et al., 2012, Dylong et al., 2013). This enables computation of the initial airflow distribution in a network. The networks can be reduced to a simpler case as in Fig. 2. The reduction method is presented below.

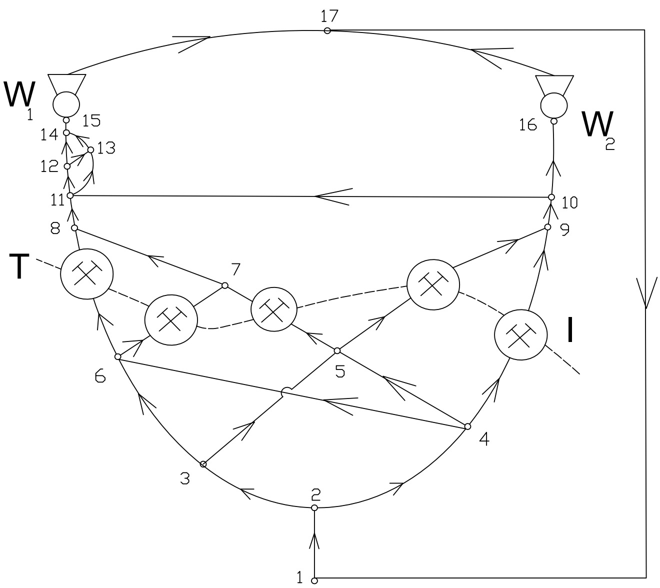

Fig. 7. The canonical diagram of a complex mining ventilation network (*own source*)

The network given in Fig. 7 has a required branch linking the subnetworks of $W1$ and $W2$ main fans. This is the 10-11 branch that corresponds to the branch $\overline{1}$ in Fig. 2. When constant airflow is assumed for working areas (branches: 6-8, 6-7, 5-7, 5-9 and 4-9), then there is only one airflow distribution (of intake air – branches below TI cross-section) which fulfills Kirchhoff's laws. Having this airflow rate it is possible to compute aerodynamic potential in the nodes: 1, 2, 10 and 11. Kirchhoff's laws allow determination of the airflow rate in the branches: 8-11 and 9-10. Following this, it is possible to determine the resistance of a substitutive branch R_s:

$$R_s = \frac{\Delta\varphi}{V_z^{\,2}} \tag{16}$$

where:

$\Delta\varphi$ – the difference in aerodynamic potential between the nodes,

V_s – substitutive airflow rate between the nodes.

For instance, to determine the resistance of substitutive branch 2-11 (corresponding to $\overline{A}$ branch in Fig. 2) the Eq. (16) is:

$$R_{2-11} = \frac{\varphi_{11} - \varphi_2}{(V_{8-11})^2} \tag{17}$$

The resistance of substitutive branch 2-10 (corresponding to $\overline{B}$ branch in Fig. 2) is analogous.

It is possible to simplify the branches: 11-12, 11-13, 12-13, 12-14, 13-14 i 14-15 to the one branch which corresponds to $\overline{2}$ branch in Fig. 2.

A lot of real mine ventilation networks fulfill the condition stated above (a single branch linking subnetworks of the main fans). Considering the structure of the network, the reduced ventilation network is identical to that given in Fig. 2 and it is possible to use the method described.

The algorithm for determination of optimal airflow distribution

1) On the basis of initial airflow distribution – to determine the values of:
   a) aerodynamic potential in the nodes which are the beginning and the end of a airstream that connects subnets of the main fans,
   b) the fan heads,
   c) the airflow rates in branches connected with the nodes mentioned in 1a.
2) On the basis of equation 16 – to determine the values of aerodynamic resistance for substitute branches. This operation leads to simplification of the network (Fig. 2).
3) On the basis of equations 5a-5d – to compute the value of additional coefficients: a, b, c and d.
4) To determine the root of a function given by equation 7. This operation leads to determination of the optimal airflow rate in a branch with an air stream connecting subnets of the main fans.
5) To determine the discharge of a fan – equations 1a and 1b.
6) To determine the necessary fan heads – equations 2a and 2b.
7) To determine the power output of the main fans – equations 3a and 3b.
8) To determine the setting of the regulation stoppings (on the basis of total pressure loss of independent airways and necessary fan head).

Example 3 – a real mining network

A practical aspect of the method is introduced in this example. Figure 8 gives an overlay of a section of a real mining network. It includes 5 intake shafts and 3 return shafts. The air from 6 mining sections was led to 2 return shafts, IV and V (Fig. 8). The total airflow rate was V = 53034 m^3/min = 883.9 m^3/s. The airflow rate in shaft IV was 21 002 m^3/min = 350 m^3/s and the airflow rate in shaft V was 32 032 m^3/min = 533.9 m^3/s. The fan heads were as follows: shaft IV Δp = 4074 Pa, and shaft V Δp = 3583 Pa. The power output for the fans at shaft IV was 1 425.9 kW, and for the fans at shaft V it was 1 912.9 kW. Thus, their total power output was 3 338.8 kW. It is evident that the airflow rate, fan head and power output are different for these shafts. This is a result of the structure of the network and the different resistances of the IV and V shafts.

The previous examples (1 and 2) showed that there is a minimum value of a function describing the total power output of the fans. Considering Fig. X, this example is shown in the branch 300 301, where the airflow rate was 630 m^3/min = 10.5 m^3/s.

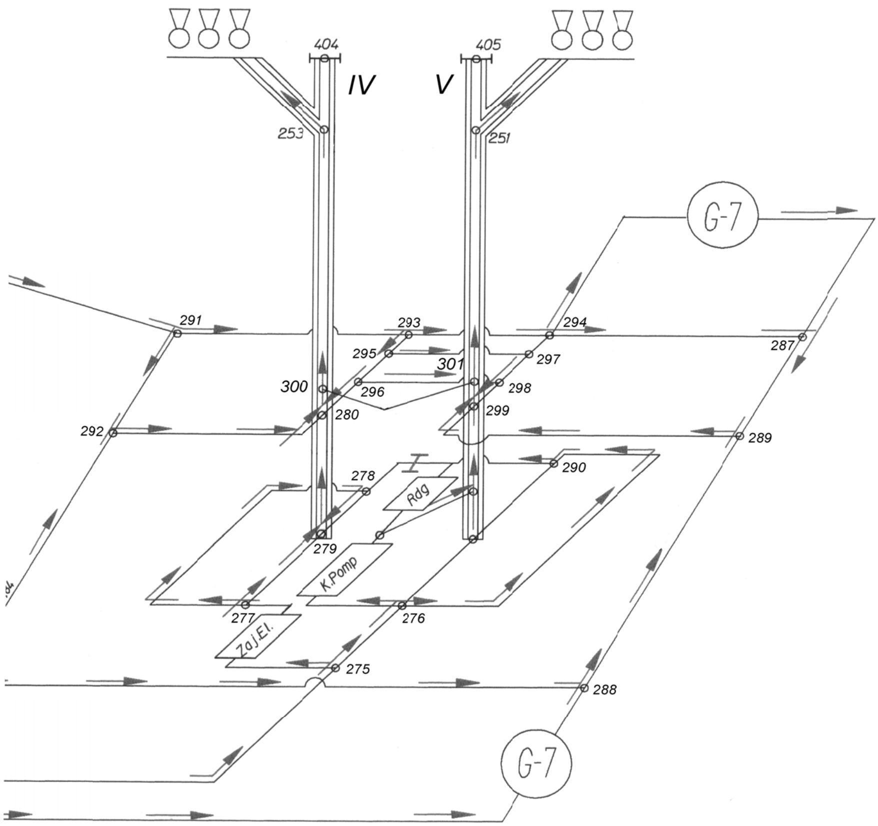

Fig. 8. The schema of a section of a real mining network (*own source*)

The substitute resistance of the branches was determined on the basis of: aerodynamic potentials from the nodes 300 and 301 (Fig. 8), airflow rates in the branches connected to these nodes, and equation 16. Equation 18 was determined as the result and is given in Fig. 9.

$$N_{u\ W1,W2} = 0.0083\left(V_1\right)^3 + 16.939\left(V_1\right)^2 + 1131.314\left(V_1\right) + 3323971$$
$$+ 0.336\left(V_1\right)^2 \left|V_1\right| + 0.336 \cdot 339.5 V_1 \left|V_1\right| \tag{18}$$

Subsequently, an optimal airflow rate for the branch 300 301 was determined as –143 m^3/s (–8580 m^3/min). This allowed the fan parameters to be determined. The results are given in Table 3. There is a comparison of the initial state and the state after application of the method.

6. Conclusions

The restructuring of mines commonly involves their interlinking. The dependent air streams are present in the merged ventilation networks. Some of these are present as return air and link the subnetworks of the main fans.

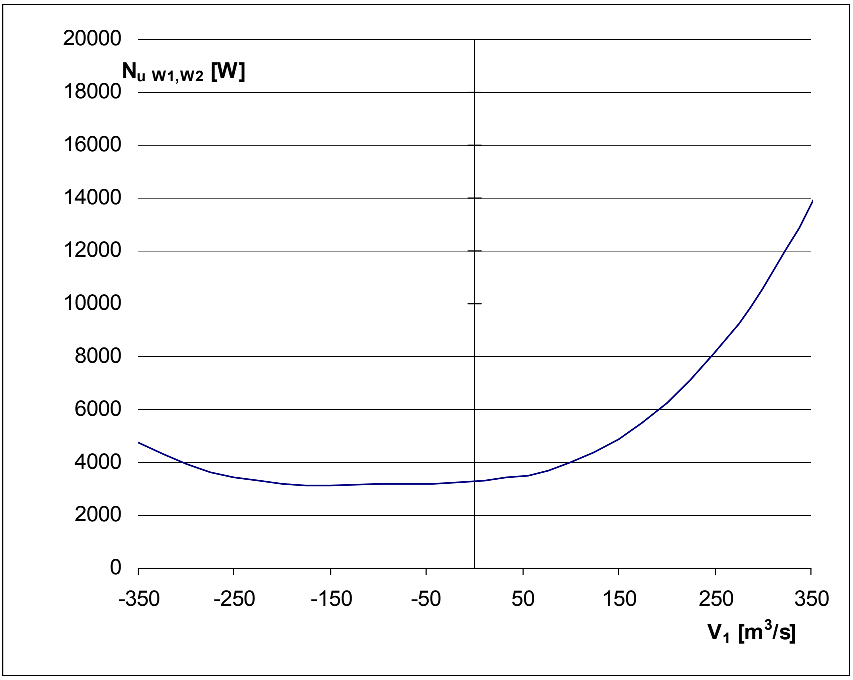

Fig. 9. Total power output of the fans at IV and V shafts and airflow rate in inter-system air stream (*own source*)

TABLE 3

The parameters of the fans at IV and V shafts in the initial state and after application of the method (own source)

Shaft IV	**Initial state**	**Optimal state**
Discharge of the fan [m^3/min] [m^3/s]	 21 002 350	 11 790 196.5
Fan head [Pa]	4 074	1 273
Power output [kW]	1 425.9	250.1
Shaft V	**Initial state**	**Optimal state**
Discharge of the fan [m^3/min] [m^3/s]	 32 032 533.9	 41 244 687.4
Fan head [Pa]	3 583	4 182
Power output [kW]	1 912.9	2 874,7
Total power output of the fans [kW]	3 338.8	3 124.8
Difference in total power output [kW]	–214 (about 6%)	
Annual energy savings [kWh/year]	2 343 300	
Annual costs savings [Euro]	335 091	

In these cases, there are many possible air distributions in a network. These fulfill "a priori" conditions of a safe airflow rate. The air distributions are achieved for different operating points (consisting of the fan head, air quantity and power output) of the fans.

1) The new algorithm presented here allows the determination of both safe and optimal air distribution. The aim of optimization is to reduce the power output of the fans while maintaining a constant level of safety in mine workings.
2) The aim of this optimization is a reduction in energy consumption by a mine. This paper has shown that the algorithm can lead to reduced energy consumption: i.e. 188 909 kWh – example 1; 1 162 364 kWh – example 2). This leads to financial savings: €27 014 – example 1; €166 218 – example 2). With respect to methane hazards, the airflow rates in branches *A* and *B* are maintained at a safe level.
3) Decreased total fan power output was achieved by an increase in air resistance (construction of a stopping), which is significantly counter-intuitive.
4) Low airflow rates in a branch with a cross-system air stream (Fig. 1, branch $\overline{1}$) indicate that the airflow is not optimal (in economic terms) (Fig. 3).
5) Usage of the algorithm for mentioned real mining network (Fig. 8) leads to 2 343 300 kWh/year energy savings what corresponds to €335 091 (Tab. 3).

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