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A RELIABLE METHOD OF COMPLETING AND COMPENSATING THE RESULTS OF MEASUREMENTS OF FLOW PARAMETERS IN A NETWORK OF HEADINGS

O PEWNEJ METODZIE UZUPEŁNIANIA I WYRÓWNYWANIA WYNIKÓW POMIARÓW PARAMETRÓW PRZEPŁYWU W SIECI WYROBISK GÓRNICZYCH

Forecasting a ventilation process is based on two factors: using a validated software (Dziurzyński et al., 2011; Pritchard, 2010) and a properly prepared database encompassing the parameters describing the flow of air and gases, compatible with the adopted mathematical model of the *VentGraph* software (Dziurzyński, 2002). With a body of measurement data and a mathematical model for computer calculations and air flow simulation at our disposal, we proceed to develop a numerical model for a chosen network of mine headings. Preparing a numerical model of a ventilation network of a given mine requires providing a collection of data regarding the structure of the network and the physical properties of its elements, such as headings, fans, or stoppings. In the case of fire simulations, it is also necessary to specify the parameters describing the seat of a fire and the properties of the rocks of which the rock mass is comprised. The methods which are currently applied to this task involve manual ventilation measurements performed in headings; the results obtained in the course of these measurements constitute a basis for determining physical parameters, such as the aerodynamic resistance of a heading, density of the flow of air, or natural depression. Experience shows that – due to difficulties regarding accessibility of headings, as well as the considerable lengths of the latter – there are some nodes and headings in mines where such measurements are not performed. Thus, an attempt was made to develop a new methodology that would provide the missing data on the basis of some other available information concerning – for example – the air density, the geometry of headings and elevations. The adopted methodology suggests that one should start with balancing the air mass fluxes within the structure of a network of headings. The next step is to compile a database concerning the pressure values in the network nodes, based on the measurement results – and provide the missing pressure values on the basis of the available results of measurements carried out in adjacent nodes, as well as the pressure value calculated on the basis of the heading geometry and the given volumetric flow rate. The present paper discusses the methodology of compensating and balancing the volumetric air flow rates within a network of headings (Chapter 2) and the methodology of determining pressure values (Chapter 3) in the nodes of the network. The developed calculation algorithms – verified by means of sample calculations performed for a selected area of a mine ventilation network – were introduced into the *VentGraph* software system. The calculation results were presented in tabular form. The Summary section discusses the minuses and pluses of the adopted methodology.

Keywords: measurements in headings, database, forecasting the ventilation process, safety of the mine ventilation system

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Podstawą prognozy procesu przewietrzania jest posługiwanie się zwalidowanym programem komputerowym (Dziurzyński i in., 2011; Pritchard, 2010) oraz poprawnie przygotowaną bazą danych zawierającą parametry opisujące przepływ powietrza i gazów, zgodną z przyjętym modelem matematycznym w programie komputerowym *VentGraph* (Dziurzyński, 2002). Dysponując bazą danych pomiarowych oraz przyjętym do obliczeń komputerowych i symulacji procesu przewietrzania modelem matematycznym przystępujemy do opracowania modelu numerycznego dla wybranej sieci wyrobisk kopalni. Przygotowanie modelu numerycznego sieci wentylacyjnej danej kopalni wymaga dostarczenia zestawu danych dotyczących struktury sieci i własności fizycznych jej elementów, tj. wyrobisk, wentylatorów, tam, a przy symulacji pożaru dodatkowo wymagane jest podanie parametrów opisujących ognisko pożaru oraz własności skał górotworu. Obecna praktyka postępowania polega na tym, że wykonuje się ręczne pomiary wentylacyjne w wyrobiskach górniczych, a uzyskane wyniki stanowią podstawę do wyznaczenia parametrów fizycznych takich jak: opór aerodynamiczny wyrobiska, gęstość przepływającego powietrza i naturalna depresja. Z uwagi na występujące trudności w dostępności wyrobisk jak również na znaczne ich długości, praktyka pokazuje, że pomiary nie są realizowane we wszystkich węzłach i wyrobiskach kopalni. Dlatego podjęto próbę opracowania nowej metodyki prowadzącej do uzupełnienia brakujących danych na podstawie innych dostępnych danych dotyczących np. gęstości powietrza, geometrii wyrobisk i kot niwelacyjnych. Z przyjętej metodyki wynika, że w pierwszej kolejności należy wykonać bilans strumieni masy powietrza w strukturze sieci wyrobisk. Następnie zbudować bazę danych ciśnień w węzłach sieci w oparciu o pomiary i uzupełnić brakujące ciśnienia na podstawie dostępnych wyników pomiarów w sąsiednich węzłach oraz ciśnienia obliczonego z wartości oporu aerodynamicznego wyznaczonego na podstawie geometrii wyrobiska i znanego strumienia objętości. W artykule przedstawiono metodykę wyrównywania i bilansowania strumieni objętości powietrza w sieci wyrobisk (rozdz. 2) oraz metodykę wyznaczania ciśnień (rozdz. 3) w węzłach sieci wyrobisk. Opracowane algorytmy obliczeń wprowadzono do systemu programów *VentGraph*, które zostały sprawdzone poprzez obliczenia dla przykładu wybranego rejonu kopalnianej sieci wentylacyjnej. Wyniki obliczeń przedstawiono w postaci tabelarycznej. W podsumowaniu omówiono wady i zalety przyjętej metodyki.

Słowa kluczowe: pomiary w wyrobiskach, baza danych, prognozowanie procesu przewietrzania, bezpieczeństwo systemu wentylacji kopalni

1. Introduction

From the perspective of mine ventilation services, a software for simulating the air flow in mine headings, once introduced into the mining pracitce (Dziurzyński & Krawczyk, 2012; Dziurzyński et al., 2014; Krawczyk & Janus, 2014;Skotniczny, 2014), becomes a user-friendly instrument for forecasting the ventilation process and the analysis of the safety of the state of ventilation.

Forecasting a ventilation process in a reliable way is based on two factors: using a validated software (Dziurzyński et al., 2011; Pritchard, 2010; Prokop et al., 2012) and a properly prepared database encompassing the parameters describing the flow of air and gases, compatible with the adopted mathematical model (Dziurzyński, 2002). With a properly prepared database and a mathematical model for computer calculations and air flow simulation at our disposal, using the effective method of solving the model equations (Krach, 2011), one can proceed to develop a numerical model for a specific network of mine headings. Preparing a numerical model of a ventilation network of a given mine requires providing a collection of data regarding the structure of the network and the physical properties of its elements, such as air splits, fans, or stoppings. In the case of fire simulations, it is also necessary to specify the parameters describing the seat of a fire and the properties of the rocks of which the rock mass is comprised. The current mining practice, adopted by all mining facilities worldwide, involves performing manual ventilation measurements in headings; the results obtained in the course of these measurements constitute a basis for determining a range of physical parameters, such as the aerodynamic resistance of a heading, density of the flow of air, or natural depression. It is also necessary to know the characteristics of the main ventilation fans.

In mine headings, the following parameters are measured: air flow velocity, transverse field of a heading, pressure and temperature in ventilation nodes. Additionally, the elevations in the spots where pressure is mesured, as well as the lengths of particular headings, are determined using excavation maps. In the existing headings, the resistance is calculated on the basis of the determined value of pressure loss w_i and the value of the volumetric flow rate Q_i, from the following formula:

$$R_i = \frac{w_i}{Q_i^2} \tag{1}$$

The pressure loss w_i can be measured directly, by means of the manometric method, or indirectly (Budryk, 1961), by means of measuring pressure, speed, temperature, and elevations. According to the adopted mathematical model describing the flow of air, there exists a relationship (2) between the pressure loss w_i, and static pressures at the opening of the air split p_1 and at the end of the air split p_2, as well as between the difference in the height of the sections z_1 and z_2 of the measurement spot at the opening and end of the heading and the difference in dynamic pressures for the speed values v_1, v_2, for which pressure loss is calculated indirectly:

$$w_i = (p_1 - p_2) + g\rho_i^s (z_1 - z_2) + \rho_i^s \frac{v_1^2 - v_2^2}{2} \tag{2}$$

The relationships (1) and (2) are the basis of the method for determining the parameters describing the ventilation network used in the *VentGraph* is based: this is the *EDTXT* module for data preparation, a specialized text editor for editing data regarding the ventilation network of a mine. A number of incorporated formulas used in basic ventilation calculations makes it easier to submit the structure of the network and measurement data in a set determined by the user. In addition to the methodology of preparing data for the numerical model, it was assumed (regarding the *EDTXT* module of the *VentGraph* system) that, for planned headings, resistance can be calculated on the basis of the formula 12. In mining practice, two methods of determining pressure loss have been used: the manometric and the barometric one. The manometric method makes it possible to perform a direct measurement of pressure loss, and involves using measuring hoses, e.g. up to 100 m long, as well as a precise manometer. As can easily be imagined, using 100 m long devices to measure a ventilation network that consists of headings whose total length is several hundred kilometers is extremely laborious. It should also be remembered that, due to the technological process, measurements with hoses are virtually impossible to perform in the area of mine walls (Biernacki & Gumiński, 1999). A case in point comes from France, where a group of eight specialists using the manometric method performed measurements for a period of 4-8 months (Frycz & Sułkowski, 1973). The currently used indirect method – the barometric one – accelerates the completion of measurements performed with the aim of calculating pressure loss. Also, the advent of innovative measuring devices considerably facilitated carrying out measurements. The progress that has occurred over the course of many years has been connected with the modernization of anemometers. The Barolux anemometer produced by Fuess – where the value of one interval, in the optical projection system, is 0.2 mm Hg, i.e. 26.6 [Pa] (Roszczynialski et al., 1992) – has been replaced with innovative, microprocessor-based, precise, µBar-type measuring devices, where measurement resolution is 1 [Pa] (Dziurzyński & Kruczkowski, 2002). Due to this fact, the accuracy of measurements improved (Krach A., 2002), and registering the measured pressure value in time made it possible to carry out simultaneous measurements in numerous underground locations (Dziurzyński & Pałka, 2002; Wasilewski, 2014).

The adopted methodology requires performing measurements in selected sections of headings within the mine ventilation network. This is done in the node area:

- the pressure value is measured in the node, at the intersection of headings,
- the air flow velocity should be measured in a section of a heading which is connected to a given node, suitable for the purpose of the measurement. It is essential that – during velocity measurements – the direction of the air flow in a given heading is established, as this is strictly connected with recording the structure of the heading network. It is accepted that the assumed direction of the air flow in a heading determines the beginning (1) and the end (2) of the *i*-th heading (air split),
- temperature values are measured with a dry-bulb and wet-bulb thermometer, in the spots where the air flow velocity is measured,
- the field of the cross-section is measured in the spot where the air flow velocity is mesured (inlets, outlets),
- on the basis of excavation maps, the elevation of the spot where pressure is measured is determined,
- throughout the duration of underground measurements, changes in the barometric pressure and temperature taken with both a dry-bulb and wet-bulb thermometer, at a selected reference node (such as the horst of a downcast shaft), are registered.

Let us now present a few remarks concerning the applied measurement methodology and the ways of determining the parameters of the numerical model:

- the air flow velocity **v** is measured by means of vane anemometers of various types. It is recommended that the method used to that end should be the one involving continuous horizontal or vertical traverse. On that basis, the mean air flow velocity is determined. The volumetric flow rate Q is calculated on the basis of the measured mean velocity and the determined section of a heading,
- the field of the heading section A, when the type of lining involved is the arch support, is usually calculated on the basis of measuring the height and width of the heading; more complex metods, like photogrammetric ones, are seldom used,
- the temperature value measured by means of a dry-bulb and wet-bulb thermometer is established with the Assmann psychrometer,
- the pressure value is measured with precise µBar-type barometers of the highest possible accuracy,
- the air density is calculated on the basis of measurements of the atmospheric pressure and the temperature taken with both a dry-bulb and wet-bulb thermometer.

The way of preparing a numerical model that has been used so far is based on manual compensation of the results of air flow measuremens performed in mines. This is very difficult and laborious, which is due to measurement errors and incomplete measurement data. There are certain mathematical methods of compensating the volumes of air flow and the potential in mine ventilation networks (Strumiński, 1971a, 1971b) – however, they require a substantial number of measurements of the velocity of the air flow, as well as of the pressure values at the beginning and end of each mine heading. On the basis of their knowledge and the practical experience gained while performing measurements and developing numerical models for operating Polish mines, the authors of the present paper conclude that, due to a large number and considerable length of headings, measurements are not performed in all nodes and headings. Additionally, as demonstrated by (Madeja-Strumińska & Strumiński, 2009), the parameters describing the flow of air change in time, which necessitates their periodic verification and updating numerical models. All these facts pose substantial difficulties when it comes to compensating measurement results and developing numerical models of mines.

It is worth noticing that, at present, researchers keep looking for still new methods of determining the parameters that have an impact on the likelihood of the occurrence of natural hazards, such as the methane hazard (Krause & Krzemień, 2014). Therefore, the purpose of this particular research is to make an attempt to develop a new methodology that would make it possible to supply the missing data on the basis of methods involving compensating the measurement results and the determined volumetric flow rate, as well as on the basis of pressure measurements carried out using some other available data concerning the air density, geometry of headings and elevations, etc. The provided formulas (1) and (2) suggest that the first step should be balancing the air mass fluxes in the heading network; then, a comprehensive database of pressure values in nodes should be compiled. Optionally, the missing pressure values in nodes may be supplied on the basis of the results of pressure measurements performed in adjacent nodes, or on the basis of the relationship involving the aerrodynamic resistance, calculated from the formula (12) for the headings omitted during measurements.

2. Balancing the air mass fluxes in a network of headings

For a node of a ventilation network, the balance of air mass fluxes is expressed in the following way:

$$\sum_{j=1}^{J} a_{i,j} Q_{M\ j} = 0 \tag{3}$$

where

- J — is the number of air splits in a ventilation network,
- $Q_{M\,j}$ — is the air mass flux in the j-th air split,
- $a_{i,j}$ — is an element of an incidence matrix showing the relationship between nodes and air splits (i – the node nuber, j – the air split number).

The relationship between the mass flux Q_M and the volumetric air flow rate Q_V is as follows:

$$Q_M = \rho_{sr} Q_V \tag{4}$$

where ρ_{sr} — is the mean density of air flowing through an air split.

The list of the results of measurements of volumetric air flow rates in the air splits of the ventilation network might not be full; moreover, the measurement results – once converted into mass fluxes – may not comply with the node balance due to measurement errors. Thus, it is necessary to compensate the values of mass fluxes in such a way that their sum in the node is 0, as specified by the formula (3). If, in the i-th node, this sum is different from 0

$$\sum_{j=1}^{J} a_{i,j} Q_{M\,j} = q_{M\,i} \tag{5}$$

corrections should be introduced into the values of the air mass fluxes in the air splits that are incidental with this particular node, proportionally to the participation of the mass flux in a given air split in the total mass flux of a given node.

$$\Delta Q_{M\,j} = -\frac{a_{i,j}\left|Q_{M_j}\right| q_{M\,i}}{\sum_{j=1}^{J}\left|a_{i,j} Q_{M_j}\right|} \tag{6}$$

As can easily be seen, the corrected values of the air mass fluxes

$$Q_{Mp\,j} = Q_{M\,j} + \Delta Q_{M\,j} \tag{7}$$

satisfy the equation of the node balance (3)

$$\sum_{j=1}^{J} a_{i,j} Q_{Mp\,j} = \sum_{j=1}^{J} a_{i,j}\left(Q_{M\,j} + \Delta Q_{M\,j}\right) = \sum_{j=1}^{J} a_{i,j} Q_{M\,j} + \sum_{j=1}^{J} a_{i,j} \Delta Q_{M\,j} =$$
$$q_{M\,i} - \sum_{j=1}^{J} \frac{a_{i,j}^2 \left|Q_{M_j}\right| q_{M\,i}}{\sum_{j=1}^{J}\left|a_{i,j} Q_{M_j}\right|} = q_{M\,i} - \frac{\sum_{j=1}^{J} a_{i,j}^2 \left|Q_{M_j}\right|}{\sum_{j=1}^{J}\left|a_{i,j} Q_{M_j}\right|} q_{M\,i} = 0 \tag{8}$$

Since the air mass fluxes in the air splits of the ventilation network are interrelated by a system of equations which, in the matrix notation, has the followin form:

$$\mathbf{A} \cdot \mathbf{QM} = 0 \tag{9}$$

where

A — is the incidence matrix showing the relationship between nodes and air splits,

QM — is the column matrix consisting of air mass fluxes in air splits,

the dependence (2.5) should be applied to all the nodes of the iterative loop, until we obtain the assumed minimum value $q_{M\,\min}$ of the variable $q_M = \max(|q_{M\,1}|,...|q_{M\,i}|,...|q_{M\,I}|)$, where $q_{M\,i}$ is calculated from the formula (5).

Now, for the nodes where the value of the mass flux is unknown as regards just one air split in all the air splits incidental with a given node, this unknown value can be calculated from the formula (3). By completing the list of air mass fluxes with the calculated values and repeating the calculations for successive nodes of the network, one can calculate other unknown volumetric flow rates in air splits. Since the air mass flux in an air split, calculated from the balance (3) for the node of just one air split end, does not have to satisfy the balance equation for the node of the other end, it is necessary to perform once more the compensation of mass fluxes in the air splits of the network.

As can be seen from the relationships given above, the information that is needed concerns the structure of the ventilation network; also, the list of mass fluxes should be known. Since the measured values are the mean velocities of air flow in air splits – which subsequently serve as a basis for calculating volumetric air flow rates – one should also know mean densities of air in air splits in order to calculate mass fluxes according to the formula (4).

3. Determining the pressure values in the nodes of the heading network on the basis of measurement results

When the volumetric air flow rate is directed from the initial node to the final node of the air split, the following equation is applied:

$$p_1 - p_2 = R_{Vb} Q_V \left| Q_V \right| + H \tag{10}$$

where

p_1, p_2 — is the static pressure at the beginning and end of the air split,
R_{Vb} — is the aerodynamic resistance of the air split for the volumetric air flow rate,
Q_V — is the volumetric flow rate in the air split,
H — is the source of pressure expressed by the formula (11):

$$H = g\rho_{sr}\Delta z - h_w \tag{11}$$

where

g — is the gravitational acceleration,
ρ_{sr} — is the mean air density in the air split,
$\Delta z = z_2 - z_1$ — is the difference between the elevations in the final and the initial node of the air split,
h_w — is the pressure increase of the fan (main or local one), directed from the beginning towards the end of the air split.

The aerodynamic resistance of the air split for the volumetric air flow rate is expressed as:

$$R_{Vb} = \lambda \rho_{sr} \frac{L}{2 D_h A^2} \tag{12}$$

where

λ — is the nondimensional resistance coefficient,
L — is the length of the air split,
D_h — is the hydraulic diameter of the air split,
A — is the area of the air split section.

The hydraulic diameter of the air split is expressed as:

$$D_h = 4\frac{A}{O} \tag{13}$$

where O — is the perimeter of the heading.

Now, the formula expressing the aerodynamic resistance of the air split shall have the following form:

$$R_{Vb} = \lambda \rho_{sr} \frac{OL}{8A^3} \tag{14}$$

For dog headings whose lining consists of sets of trough arches, the following formula expressing the resistance of the heading R_f specified in the norm BN-75/0422-02 can be applied:

$$R_f = 100\, r_f \frac{l}{100} k \tag{15}$$

where

- $100\, r_f$ — is the resistance of a 100 m long straight section of a dog heading lined with sets of trough arches placed at the intervals of 0,9÷1,2 m, of a constant cross section, equipped with rail tracks, a water pipeline, a compressed air pipeline and wires, with no transport devices,
- l — is the length of the dog heading [m],
- k — is the coefficient dependent on the condition of the heading and its equipment, $k = 1 \div 2$

The value of the resistance $100\, r_f$, depending on the area of the heading section A, can be read from a diagram specified in the norm. The diagram was estimated by means of the formula

$$100\, r_f = 3{,}338232279 A^{-2{,}52447408} \tag{16}$$

with the coefficient of determination $R^2 = 0{,}998663$.

For an air mass flux, the following relationship is adopted:

$$p_1 - p_2 = R_{Mb} Q_M \left| Q_M \right| + H \tag{17}$$

where

- Q_M — is the air mass flux in the air split,
- R_{Mb} — is the aerodynamic resistance of the air split to the air mass flux.

The aerodynamic resistance of the air split to the air mass flux is related to the resistance to the volumetric flow rate in the following way:

$$R_{Mb} = \frac{R_{Vb}}{\rho_{sr}^2} \tag{18}$$

When the relationship (14) is taken into account, the formula given above assumes the following form:

$$R_{Mb} = \lambda \frac{OL}{8 \rho_{sr} A^3} \tag{19}$$

If the pressure p_2 in the node at the end of the j-th air split is known, as well as the volumetric flow rate Q_{Vj} or the air mass Q_{Mj} in this particular air split, then – with the help of the resistance coefficient and geometric quantities of the air split – one can estimate the aerodynamic resistance of the air split $R_{Vb\,j}$ or $R_{Mb\,j}$. Then, on the basis of the relationship (10) or (14), the pressure in the initial node of the air split can be calculated:

$$p_1 = p_2 + R_{V/M\,b\,j} Q_{V/M\,j} \left| Q_{V/M\,j} \right| + H_j \tag{20}$$

When the calculations are performed for the j-th air split

$$\Delta P_j = R_{V/M\,b\,j} Q_{V/M\,j} \left| Q_{V/M\,j} \right| + H_j \tag{21}$$

where

$$H_j = g\rho_{sr\,j} \Delta z_j - h_{w\,j} \tag{22}$$

the following relationship is obtained for the i-th node incidental with the j-th air split:

$$p_i = p_k + a_{i,j} \Delta P_j \tag{23}$$

where $k = w_{2\,j}$ when $a_{i,j} = 1$, in which case p_i is the pressure in the initial node of the j-th air split, and $k = w_{1\,j}$ when $a_{i,j} = -1$, in which case p_i is the pressure in the final node of this particular air split, and $a_{i,j}$ is the element of the incidence matrix **A**, with $w_{1\,j}$ and $w_{2\,j}$ being the elements of the list of air splits **W1**, **W2**.

For the incidence matrix **A**, it was assumed that $a_{i,j} = 1$ when the i-th node is the initial node of the j-th air split, and $a_{i,j} = -1$ when the i-th node is the final node of this air split.

When the i-th node, whose pressure value p_i is unknown, adjoins several nodes of known pressure values, and when it is connected to these nodes by means of air splits for which the value of the pressure difference Δp_j can be estimated, the values of pressure p_i in the i-th node, calculated from pressure values in various adjoining nodes, can be manifold. This is due to measurement errors and uncertainty regarding the pressure difference Δp_j. Therefore, for the sake of further calculations, the mean pressure value was adopted:

$$p_i = \frac{\sum_{j=1}^{J} \left| a_{2\,i,j} a_{1\,k,j} \right| \left(p_k + a_{2\,i,j} \Delta P_j \right)}{\sum_{j=1}^{J} \left| a_{2\,i,j} a_{1\,k,j} \right|} \qquad k = \sum_{l=1}^{I_1} l \left| a_{1\,l,j} \right| \tag{24}$$

where $a_{1\,l,j}$ and $a_{2\,i,j}$ are the elements of matrices **A1** and **A2**, created on the basis of the incidence matrix **A** in accordance with the following pattern:

- make a copy of the matrix **A** and record it as **A1**;
- copy – to the matrix **A2** - these rows of the matrix **A1** which correspond to the nodes for which the elements p_i of the pressure table **P** equal 0;
- zero the copied rows in the matrix **A1** and record their numbers.

Now, with the list of volumetric flow rates in the air splits **QV** and the list of pressure values in the network nodes **P** at our disposal, the resistance values in the network air splits can be calculated:

$$R_{V\,j} = \frac{p_{i1} - p_{i2} - g\rho\Delta z_j + h_w}{\left|Q_{V\,j}\right| Q_{V\,j}} \tag{25}$$

where the indices $i1$ and $i2$ are calculated from the list of air splits **W1**, **W2** for the j-th air split: $i1 = w_{1\,j}$, $i2 = w_{2\,j}$.

Negative resistance values suggest that the pressure values in nodes were measured or calculated in a wrong way, as the results of measurements and calculations of the volumetric air flow rates are more reliable. Calculations performed for the mine ventilation network on the basis of incomplete database demonstrated that better results (i.e. with fewer negative resistance values) are obtained when weighted means are applied while calculating the missing pressure values in nodes.

$$p_i = \frac{\sum_{j=1}^{J} \left|a_{2\,i,j} a_{1\,k,j}\right| \left(p_k + a_{2\,i,j}\Delta P_j\right) Q_{V\,j}^2}{\sum_{j=1}^{J} \left|a_{2\,i,j} a_{1\,k,j}\right| Q_{V\,j}^2} \qquad k = \sum_{l=1}^{I_1} l \left|a_{1\,l,j}\right| \tag{26}$$

4. Validating the new algorithms of the software for data editing

In order to validate the methodology for completing and compensating the results of measurements of the volumetric air flow rates in air splits and pressure values in the nodes of the mine ventilation network (cf. Fig. 1), discussed in the previous chapter, appropriate calculations were performed – step by step – according to the developed methodology, for the example provided

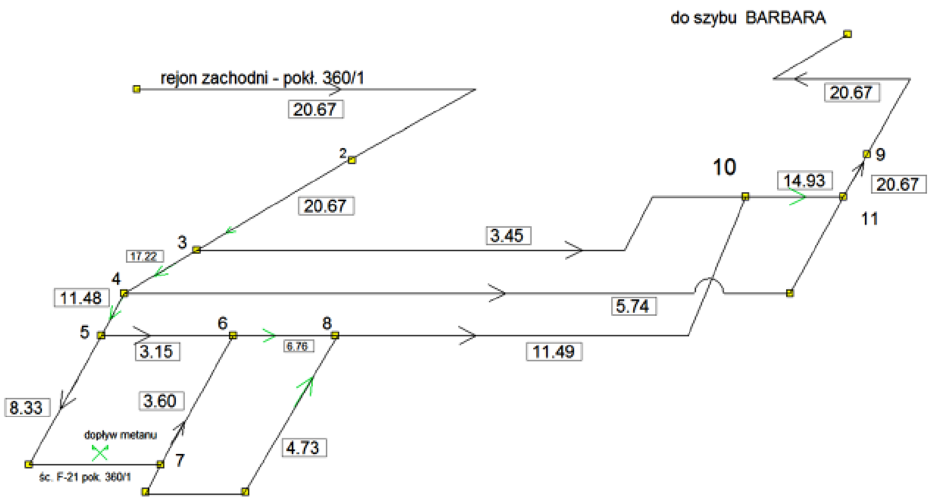

Fig. 1. A sample structure of a ventilation network of the F-21 wall area of the „M” mine

below. The results of the calculations were subsequently compared with the results obtained using the *VentGraph* software.

The rectangles contain the values of the volumetric air flow rates in air splits – given in m^3/s, and calculated by means of the ***VentGraph*** software.

The structure of a sample ventilation network is presented as the list of air splits **W1**, **W2**, shown in the form of a table (cf. Table 1).

TABLE 1

Air split no.	Node no. – inlet W1	Node no. – outlet W2
1	9	1
2	1	2
3	2	3
4	3	4
5	4	5
6	5	7
7	7	8
8	8	10
9	10	11
10	11	9
11	4	11
12	5	6
13	7	6
14	6	8
15	3	10

On the basis of the list of air splits **W1**, **W2**, the incidence matrix **A**, representing the relationship between nodes and air splits, was created (cf. Table 2).

TABLE 2

n\as	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	**-1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	**-1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	**-1**	**1**	0	0	0	0	0	0	0	0	0	0	**1**
4	0	0	0	**-1**	**1**	0	0	0	0	0	**1**	0	0	0	0
5	0	0	0	0	**-1**	**1**	0	0	0	0	0	**1**	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	**-1**	**-1**	**1**	0
7	0	0	0	0	0	**-1**	**1**	0	0	0	0	0	**1**	0	0
8	0	0	0	0	0	0	**-1**	**1**	0	0	0	0	0	**-1**	0
9	**1**	0	0	0	0	0	0	0	0	**-1**	0	0	0	0	0
10	0	0	0	0	0	0	0	**-1**	**1**	0	0	0	0	0	**-1**
11	0	0	0	0	0	0	0	0	**-1**	**1**	**-1**	0	0	0	0

In order to validate the algorithm for compensating and completing the results of the measurements of volumetric flow rates in the database, obtained with the*VentGraph* software, the list of air densities **RO** and the list of volumetric flow rates **QV** were provided in Table 3. Subsequently, air mass fluxes were calculated and put on the **QM** list. For the air splits 1, 2, 6, 8, 10, 11, 12, 13, and 15, the values were removed from the database; instead, the values Q_{Vj} = 600000 m^3/s and $Q_{Mj} = \rho_j Q_{Vj}$ were put on the lists **QV** and **QM**, respectively, which meant that no measurement was performed for this particular air split (Table 3). It was assumed that the positive result of the validation process would be the compatibility of the values of volumetric flow rates in air splits calculated according to the validated algorithm with the appropriate values of the volumetric flow rates from the *VentGraph* software database.

TABLE 3

Air split no.	Air density RO	Volumetric flow rate QV	Mass flux QM
	kg/m^3	m^3/s	kg/s
1	1,2	600000	720000
2	1,2	600000	720000
3	1,2	20,67	24,804
4	1,2	17,22	20,664
5	1,2	11,48	13,776
6	1,2	600000	120000
7	1,2	4,73	5,676
8	1,2	600000	720000
9	1,2	14,93	17,916
10	1,2	600000	720000
11	1,2	600000	720000
12	1,2	600000	720000
13	1,2	600000	720000
14	1,2	6,76	8,112
15	1,2	600000	720000

On the basis of the list of air mass fluxes **QM**, two tables were compiled: the table **TB** with the numbers of air splits with known values of mass fluxes (6 air splits) and the table **TBN** with the numbers of air splits with unknown values of air mass fluxes (9 air splits).

The **TBN** table with the air splits with unknown air mass flux values and the **A** incidence table were used to create the **TW** table with the numbers of nodes with known values of air mass fluxes in all the incident air splits (0 nodes) and the **TWN** table with the numbers of nodes with unknown values of air mass fluxes in at least one air split (11 nodes). Subsequently, the air mass fluxes in the network nodes were balanced, and the missing air mass fluxes were calculated.

Below, in Table 4, the **QM** list of air mass fluxes was shown, with the air splits with unknown values of air mass fluxes (72,000) marked with bold print (column 2), together with the list with supplied missing flux values (column 3).

TABLE 4

Air split no.	Q_M kg/s	Q_M kg/s
1	**2**	3
1	720000	24,804
2	720000	**24,804**
3	24,804	24,804
4	20,664	20,664
5	13,776	13,776
6	**720000**	120000
7	5,676	5,676
8	**720000**	**13,788**
9	17,916	17,916
10	**720000**	**24,804**
11	**720000**	**6,888**
12	**720000**	120000
13	**720000**	120000
14	8,112	8,112
15	**720000**	**4,14**

As a result of the application of the software procedures, information was returned that the set of air splits with known air mass flux values is too small, which makes it impossible to calculate the fluxes in the remaining air splits. Thus, in Table 4, **QM**, the value of the air mass flux in air split no. 6 was added (column 2), and, subsequently, further calculations were performed. In the course of these calculations, the missing values of the air mass fluxes in air splits no. 12 and 13 were obtained (column 3). The result of the calculations was shown in Table 5.

TABLE 5

Air split no.	Q_M kg/s	Q_M kg/s
1	**2**	**3**
1	**24,804**	**24,804**
2	**24,804**	**24,804**
3	24,804	24,804
4	20,664	20,664
5	13,776	13,776
6	**12,372**	**12,372**
7	5,676	5,676
8	**13,788**	**13,788**
9	17,916	17,916
10	**24,804**	**24,804**
11	**6,888**	**6,888**
12	120000	**1,404**
13	120000	**6,708**
14	8,112	8,112
15	**4,14**	**4,14**

Subsequently, balancing the air mass fluxes in the network nodes was repeated. After the mass fluxes were converted to volumetric air flow rates, they were compared with the results of the calculations performed for this particular example, using the *VentGraph* software. The effect of these calculations was presented in Table 6.

TABLE 6

Air split no.	Volumetric flow rate m³/s		Difference m³/s
	Q_{V1}	Q_{V2}	$Q_{V1} - Q_{V2}$
1	20,67	20,67	0
2	20,67	20,67	0
8	11,48	11,49	–0,01
10	20,67	20,67	0
11	5,740	5,740	0
12	1,17	1,17	0
13	5,58	5,58	0
15	3,45	3,45	0

- Q_{V1} – the volumetric flow rate calculated with the ***VentGraph*** software,
- Q_{V2} – the volumetric flow rate calculated from the formula $Q_{V2} = Q_M/\rho$, where Q_M is the air mass flux calculated for this particular example, and r is the density of air from the database concerning this particular example

The next stage of the calcualtions involved validating the algorithm for determining the pressure values in the network nodes. The database to be used in the calculation process included the list of air splits **W1**, **W2**, the list of resistance values of air splits **R**, the list of volumetric air flow rates **QV**, the list of air densities **RO**, the list of differences between the elevations at the beginning and end of an air split **DZ**, the list of main and local fan pressure values **HW**, and the list of pressure values in the nodes **P** from the *VentGraph* software (the data was presented in Table 7). Then, from the pressure list **P**, the pressure values in nodes no. 3, 8, and 10 were removed (cf. Table 8), and replaced with the „0” pressure value. It was assumed that a positive outcome of the validation process would be compatibility of the missing pressure values in the network nodes calculated according to the validated algorithm with the corresponding pressure values from the *VentGraph* database.

TABLE 7

Air split no.	Node no. – inlet W1	Node no. – outlet W2	Air split resistance R	Volumetric air flow rate QV	Air density RO	z2 – z1 DZ	Fan pressure HW
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
			kg/m⁷	m³/s	kg/m³	m	Pa
1	9	1	0.500	20.67	1.2	360.0	2965
2	1	2	0.693	20.67	1.2	–482.0	0.0
3	2	3	2.856	20.67	1.2	13.0	0.0
4	3	4	0.088	17.22	1.2	–3.0	0.0
5	4	5	0.214	11.48	1.2	–18.0	0.0

1	2	3	4	5	6	7	8
6	5	7	0.233	10.31	1.2	–38.0	0.0
7	7	8	0.3758	4.73	1.2	48.0	0.0
8	8	10	0.852	11.48	1.2	15.0	0.0
9	10	11	0.81	14.93	1.2	0.0	0.0
10	11	9	2.00	20.67	1.2	105.0	0.0
11	4	11	10.76	5.74	1.2	7.0	0.0
12	5	6	20.00	1.17	1.2	0.0	0.0
13	7	6	0.091	5.58	1.2	38.0	0.0
14	6	8	0.122	7.13	1.2	10.0	0.0
15	3	10	16.80	3.00	1.2	4.0	0.0

TABLE 8

Node no.	**Pressure** **P**
	Pa
1	100000
2	105378
3	0
4	104014
5	104197
6	104170
7	104620
8	0
9	101486
10	0
11	103577

Next, the **A1**, **A2** and **TW2** tables were created. This was done by transferring the contents of the incidence table **A** to the table **A1**, and copying the rows corresponding to the nodes for which no pressure values were measured (i.e. the rows no. 3, 8, and 10) to the table **A2**. The numbers of these rows were put in the table **TW2**. In the table **A1** ,the rows copied to the table **A2** (i.e. the rows no. 3, 8, and 10) were zeroed. The unknown node pressure values were established as a result of performing calculations according to the algorithm presented in Chapter 4, step by step. The complete list of pressure node values **P** is shown in Table 9.

TABLE 9

Node no.	**Pressure** **P**
	Pa
1	**2**
1	100000
2	105378
3	104006
4	104014

1	2
5	104197
6	104170
7	104620
8	104047
9	101486
10	103758
11	103577

TABLE 10

Node no.	Pressure [Pa]		Differential pressure [Pa]
	p_1	p_2	$p_1 - p_2$
3	104005	104006	–1
8	104047	104047	0
10	103758	103758	0

The results of the calculations of the missing pressure values were compared with the values obtained with the *VentGraph* software. The effect of the calculations was presented in Table 10.

Subsequently, the resistance of air splits was calculated. The resistance value of the *j*-th air split was calculated from the following formula:

$$R_j = \frac{p_{i1} - p_{i2} - g\rho_j \Delta z_j + h_{wj}}{\left|Q_{Vj}\right| Q_{Vj}} \qquad i1 = w1_j \qquad i2 = w2_j \tag{27}$$

where

p_{i1}, p_{i2} — are the pressure values in nodes no. $i1$, $i2$, (Table 11A),
$w1_j$, $w2_j$ — are the numbers of the inlet and outlet nodes of the *j*-th air split (columns **W1** and **W2** in Table 11B),
ρ_j — is the density of air in the *j*-th air split (column **RO** in Table 11B),
Δz_j — is the difference between the elevations at the outlet and inlet of the *j*-th air split (column **DZ** in Table 11B),
h_{wj} — is the fan pressure in the *j*-th air split (column **HW** in Table 11B),
Q_{Vj} — is the volumetric air flow rate in the *j*-th air split (column **QV** in Table 11B).

TABLE 11A

Node no. *i*	Pressure P		Node no. *i*	Pressure P
	Pa			Pa
1	100000		7	104620
2	105378		8	104047
3	104005		9	101486
4	104014		10	103758
5	104197		11	103577
6	104170			

TABLE 11B

Air split no. *j*	Node no. – inlet W1	Node no. – outlet W2	Volumetric air flow rate QV	Pressure P1	Pressure P2	Air density RO	Difference between elevations $z_2 - z_1$ DZ	Fan pressure HW	Air split resistance R
			m^3/s	Pa	Pa	m^3/s	m	Pa	kg/m^7
1	9	1	20.67	101486	100000	1.2	360.0	2965	0.499
2	1	2	20.67	100000	105378	1.2	–482.0	0.0	0.693
3	2	3	20.67	105378	104005	1.2	13.0	0.0	2.855
4	3	4	17.22	104006	104014	1.2	–3.0	0.0	0.089
5	4	5	11.48	104014	104197	1.2	–18.0	0.0	0.219
6	5	7	10.31	104197	104620	1.2	–38.0	0.0	0.229
7	7	8	4.73	104620	104047	1.2	48.0	0.0	0.355
8	8	10	11.49	104047	103758	1.2	15.0	0.0	0.852
9	10	11	14.93	103758	103577	1.2	0.0	0.0	0.812
10	11	9	20.67	103577	101486	1.2	105.0	0.0	2.001
11	4	11	5.74	104014	103577	1.2	7.0	0.0	10.762
12	5	6	1.17	104197	104170	1.2	0.0	0.0	19.724
13	7	6	5.58	104620	104170	1.2	38.0	0.0	0.086
14	6	8	6.76	104170	104047	1.2	10.0	0.0	0.116
15	3	10	3.45	104006	103758	1.2	4.0	0.0	16,880

The results of calculations of the resistance values of air splits R_1 were compared with the resistance values R_2 from the *VentGraph* software database for this particular example. The effect of the calculations was presented in Table 12.

TABLE 12

Air split no.	Air split resistance kg/m^7		Difference kg/m^7
	R_1	R_2	$R_1 - R_2$
1	0.500	0.499	0.001
2	0.693	0.693	0
3	2.856	2.855	0.001
4	0.088	0.089	–0.001
5	0.214	0.219	–0.005
6	0.233	0.229	0.004
7	0.3758	0.355	0.003
8	0.852	0.852	0
9	0.810	0.812	–0.002
10	2.000	2.001	–0.001
11	10.760	10.762	–0.002
12	20.000	19.724	0.276
13	0.0910	0.086	0.014
14	0.122	0.116	0.006
15	16.800	16.880	–0.080

As demonstrated by Table 12, the calculated resistance values correspond – with satisfactory accuracy – to the values from the numerical model of the *VentGraph* software.

5. Summary

Compensating the results of measurements carried out in a network of headings – in the context of developing a numerical model – still poses a considerable challenge both for science and mining practice. The available publications discussing the topic in question are scarce, which prompts further research, especially in the light of the application of new measurement devices, as well as practical experiences. The methodology of completing and balancing the unmeasured values of volumetric flow rates and pressure values, discussed in the present paper, demonstrated that the procedures developed for the sake of it work properly. During the validation process of the code of the algorithms of the procedure of completing and compensating measurement results, the results of calcualtions performed „step by step" were compared with the database of the numerical model and with the results of the calcualtions carried out with the *VentGraph* software. The developed methodology of completing and compensating volumetric flow rates is based on the node equation (3). When the mass fluxes converted into volumetric flow rates do not satisfy the balance in the node, the relationship (7) should be applied to all the nodes in

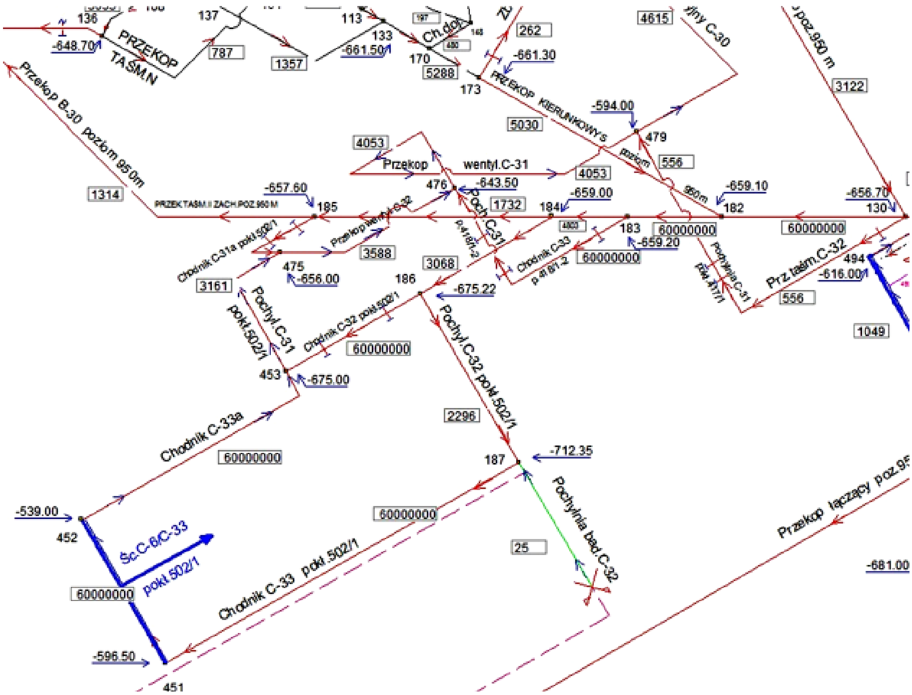

Fig. 2. A spatial diagram of the C-6 wall area in the „K" mine; the rectangles include measured and missing volumetric flow rate values

the iterative loop – according to the formulas (5) and correction (6) – until the assumed minimal value of the highest q_M value, specified in the formula (5), is obtained.

Below, the authors provided a usage example concerning the new procedures of compensating the measurement results with the *VentGraph* software (into which these new procedures were introduced), for an actual network of an area of the „K" mine. The effect of the procedure application is presented in the two figures below.

Figure 2 shows a section of the ventilation network of the C-6 wall area in the „K" mine. The rectangles next to the heading symbols – with the number 60000000 – inform that in this particular spot no mean air velocity was measured during ventilation measurements, and that the value of the volumetric flow rate for this particular heading is missing from the database of the numerical model.

The analysis of Figure 2, and Figure 3 in particular, shows that – in the rectangles for which the values of the volumetric flow rate are given – the procedures of completing and compensating the balance of the volumetric flow rate for this particular area yielded a desirable effect.

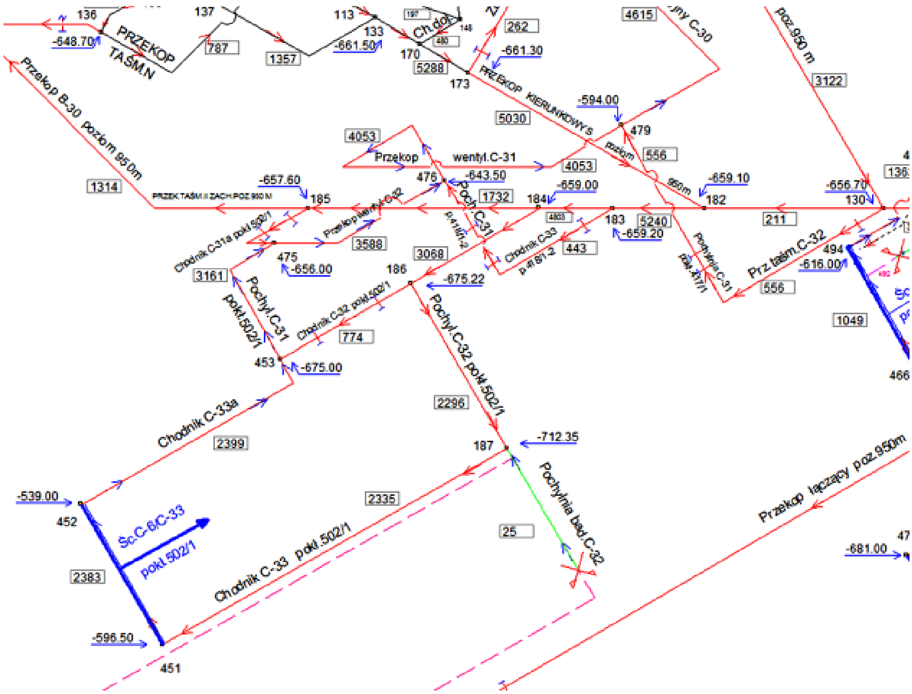

Fig. 3. A spatial scheme of the C-6 wall area of the „K" mine; the rectangles include measured and supplied volumetric flow rate values

The other example presenting the application of the method for completing the missing pressure values concerns the actual ventilation network of the „K" mine, for which the numerical model had to be updated due to the fact that mining activity was initiated in a new area of the B-8 wall in the coal bed no. 510.

The ventilation network of the „K” mine consists of 465 air splits and 317 nodes. After measurements were performed, it turned out that, for a lot of nodes, no pressure values were recorded. This situation is presented in the first EDTXT sheet (cf. Fig. 4) of the *VentGraph* software: for the nodes 100-109, there are no pressure values (the column on the left side of the sheet from Fig. 4). After completing and compensating the pressure values, the calculated pressure value for node no. 100 was shown in Fig. 5; for the remaining nodes, pressure values were also calculated, which is marked with the ~ symbol next to the number of each node.

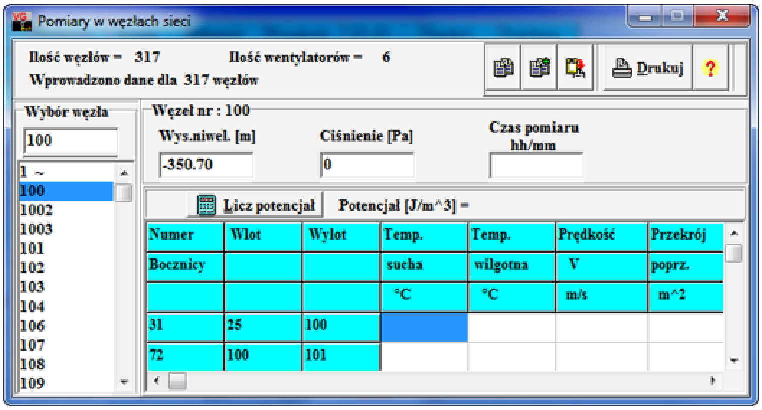

Fig. 4. An EDTXT sheet with data for particular nodes – there is no pressure value for node no. 100, which was marked with „0”

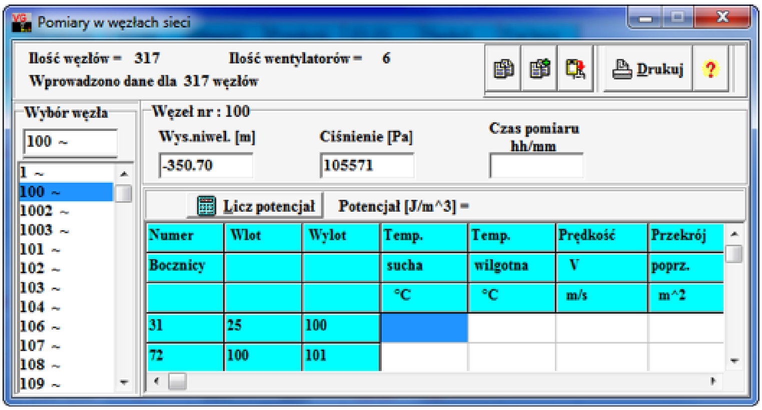

Fig. 5. An EDTXT sheet with data for particular nodes – the pressure value for node no. 100, p_{100} = 105571 [Pa], was supplied

As for completing and compensating pressure values, the issue in question becomes more complex, since the pressure values determined according to the algorithm given do not always yield the correct result. This is demonstrated by the negative value of the aerodynamic resistance determined for a known direction of the air flow. This means that the determined pressures p_1 and p_2 – in relation to the know values of the elevations and the density of the air flow – do not yield a positive value of the pressure loss. When this is the case, one should check if the elevations entered into the database are correct; if this does not give a satisfactory result, one might consider repeating the measurements in the area of the node in question, or a group of connected nodes.

To sum up, the effects of the discussed research can be used in practice, and the developed method of completing and compensating measurement results yields a satisfactory outcome, which prompts further modification of the algorithms for compensating measurement results. This, however, requires that the research should be continued. At this point, it needs to be said that an equally important question is determining the uncertainty of measurements of particular measured parameters. At present, researchers know of the uncertainty connected with determining the volumetric flow rate using manual anemometers; depending on the applied measurement device, this uncertainty is estimated to be between 9.4% and 14.7% of the value established by means of the „anemometer at the cross-section" method (Krach, 2009). When it comes to determining the measurement uncertainty, one must be prepared that its value may be between 1.5% and 3.7%. However, when the object of a measurement performed with two barometers is a low differential pressure, and when the measured pressure values fluctuate considerably, the relative uncertainty may exceed 100% many times over (Krach, 2002). It should be noted again that performing correct measurements in the headings of a working mine is a laborious task, requiring a high level of thoroughness both during the preparation stage and the actual measurements.

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