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OPTIMIZATION OF FORCED AIR FLOW BY THE COMPARISON OF POSITIVE AND NEGATIVE REGULATIONS IN MINE VENTILATION NETWORK

OPTYMALIZACJA WYMUSZONEGO ROZPŁYWU POWIETRZA W KOPALNIANYCH SIECIACH WENTYLACYJNYCH – PORÓWNANIE REGULACJI DODATNIEJ I UJEMNEJ

Mining ventilation should ensure in the excavations required amount of air on the basis of determined regulations and to mitigate various hazards. These excavations are mainly: longwalls, function chambers and headings. Considering the financial aspect, the costs of air distribution should be as low as possible and due to mentioned above issues the optimal air distribution should be taken into account including the workers safety and minimization of the total output power of main ventilation fans. The optimal air distribution is when the airflow rate in the mining areas and functional chambers are suitable to the existing hazards, and the total output power of the main fans is at a minimal but sufficient rate.

Restructuring of mining sector in Poland is usually connected with the connection of different mines. Hence, dependent air streams (dependent air stream flows through a branch which links two intake air streams or two return air streams) exist in ventilation networks of connected mines. The zones of intake air and return air include these air streams. There are also particular air streams in the networks which connect subnetworks of main ventilation fans. They enable to direct return air to specified fans and to obtain different airflows in return zone. The new method of decreasing the costs of ventilation is presented in the article.

The method allows to determine the optimal parameters of main ventilation fans (fan pressure and air quantity) and optimal air distribution can be achieved as a result. Then the total output power of the fans is the lowest which makes the reduction of costs of mine ventilation.

The new method was applied for selected ventilation network. For positive regulation (by means of the stoppings) the optimal air distribution was achieved when the total output power of the fans was 253.311 kW and for most energy-intensive air distribution it was 409.893 kW. The difference between these cases showed the difference in annual energy consumption which was 1 714 MWh what was related to annual costs of fan work equaled 245 102 Euro. Similar values for negative regulation (by means of auxiliary fans) were: the total output power of the fans 203.359 kW (optimal condition) and 362.405 kW (most energy-intensive condition). The difference of annual energy consumption was 1 742 MWh and annual difference of costs was 249 106 Euro. The differences between optimal airflows considering positive and negative regulations were: the total output power of fans 49.952 kW, annual energy consumption 547 MWh, annual costs 78 217 Euro.

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

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Przewietrzanie podziemnej kopalni powinno zapewnić dostarczenie odpowiedniej do poziomu zagrożeń i zgodnej z przepisami prawa ilości powietrza do wyrobisk górniczych w których znajdują się miejsca pracy górników. Takimi wyrobiskami są np. ściany i komory funkcyjne. Ze względów finansowych korzystne jest, aby takie przewietrzanie odbywało się przy jak najmniejszym koszcie. Z tego powodu celowe jest poszukiwanie optymalnego rozpływu powietrza uwzględniającego bezpieczeństwo pracy górników jak i minimalizującego moc wentylatorów głównego przewietrzania.

Podczas prowadzonej w Polsce restrukturyzacji górnictwa często dochodzi do łączenia kopalń. Z tego powodu w sieciach wentylacyjnych połączonych kopalń występują zależne prądy powietrza, zarówno w strefie powietrza doprowadzanego (świeżego) jak i odprowadzanego (zużytego). W takich sieciach występują również szczególne prądy powietrza łączące podsieci wentylatorów głównego przewietrzania. Pozwalają one na manewrowanie (kierowanie) rozdziałem powietrza odprowadzanego (zużytego) na poszczególne wentylatory, a poprzez to uzyskiwanie różnych rozpływów powietrza w strefie zużytej. W artykule ukazano rezultaty badań nad takimi sieciami. Wskazano nową metodę pozwalającą na obniżenie kosztów wentylacji.

Przedstawiona w pracy metoda pozwala na wyznaczenie parametrów wentylatorów głównego przewietrzania (spiętrzenia i wydajności), przy których uzyskuje się optymalny rozpływ powietrza. Wartość sumarycznej mocy użytecznej wentylatorów głównego przewietrzania jest wtedy najniższa, efektem czego jest obniżenie kosztów wentylacji kopalni.

Według nowej metody wykonano obliczenia dla przykładowej sieci wentylacyjnej. Przy regulacji dodatniej (za pomocą tam regulacyjnych) optymalny rozpływ powietrza uzyskiwany był przy sumarycznej mocy użytecznej wentylatorów wynoszącej 253 311 W, zaś dla najmniej korzystnego rozpływu powietrza wartość ta wynosiła 409 893 W. Różnica pomiędzy tymi rozpływami przekładała się na roczną różnicę w zużyciu energii wynoszącą 1714 MWh oraz na roczna różnicę kosztów pracy wentylatorów 245 102 Euro. Analogiczne wartości dla regulacji ujemnej (z uwzględnieniem pracy wentylatorów pomocniczych) wynosiły: sumaryczne moce użyteczne wentylatorów 203 359 W (stan optymalny) i 362 405 W (stan najmniej korzystny), roczna różnica zużycia energii 1742 MWh i roczna różnica kosztów 249 106 Euro. Różnice pomiędzy rozpływami optymalnymi przy regulacji dodatniej i ujemnej wynosiły: dla sumarycznej mocy użytecznej 49 952 W, dla rocznego zużycia energii 547 MWh, dla rocznych kosztów 78 217 Euro.

Słowa kluczowe: kopalniana sieć wentylacyjna, rozpływ wymuszony powietrza, koszty przewietrzania, optymalizacja rozpływu powietrza w sieci kopalnianej, bezpieczna wentylacja kopalń, zależne prądy powietrza

1. Introduction

Ventilation of the mine is a crucial part of prevention against: methane hazard, fire hazard, dust hazard and thermal hazard (Szlązak & Kubaczka, 2012; Knechtel, 2011; Dziurzyński et al., 2012; Zhong et al., 2003; Szlązak et al., 2013; Liu et al., 2017). Proper ventilation of an underground mine should assure the required amount of air to the excavations where miners work. This amount of air should be determined on the basis of the regulations and the level of hazards. These places are as follows: excavations, chambers and headings.

Total energy consumption in Poland in all sectors was 150 TWh in 2015, but in 2016 it increased to 164 TWh (PSE, 2016). The energy consumption in Polish mining was increasing gradually from 7 395 GWh in 2008 to 8 687 GWh in 2015 (Kicki & Jeziorowska, 2015). One can state that mining activities consume over 5% of total energy consumption at the national level and it is crucial for national energy economy. According to (Carvalho & Millar, 2012) in RPA, the USA and Brazil mining consumes approximately 3-6% of total generated electricity. Iha A.K.(Jha, 2017) states that average cost of the ventilation of the underground mine might exceed the third of the total operating costs. According to (Jesviet et al., 2015, Jesviet & Szekeras, 2016) the cost of mine ventilation often exceeds 25%. In the article (Nikolaev et al., 2017) it is said that from 30% to 50% of electric energy delivered to the mine is used for ventilation purposes. Mielli & Bongiovanni stated that approximately 15-40% of the energy delivered is connected with mine ventilation (Mieli & Bongiovanni, 2013). It can be pointed out that ventilation of the mine is significantly energy consuming comparing to total energy consumption in mines. It causes that the changes of mine ventilation may reduce the energy consumption significantly. As a result the operational costs of mine may be lowered. According to Crittenden (Crittenden, 2016) cost reduction can be achieved by: optimization of ventilation systems, keeping sufficient amounts of air in the excavations and improvement of the working of fans. In one case presented by E.D. Souza (Souza, 2017) the optimization of ventilation system (implementing the devices which regulate the airflow in ventilation network) and working of fans made the operating cost lower by 7% (25 630$). Similar examinations were carried out by N. Szlązak and D. Obracaj (Szlązak & Obracaj, 2017). Du Plessis, Marx and Nell (Du Plessis et al., 2014) presented the method which reduces the energy consumption in ventilation of the mine. The optimization of ventilation system should not only reduce the ventilation costs of the mine but also keep sufficient amounts of air in the excavations.

In the article there are results of research into mining ventilation network which include ventilation branches connecting the subnetworks of the main fan. These air streams can be treated like cross-system airflow. For this type of ventilation networks, studies on the optimization of air distribution have not been carried out yet. This brand new method allows to decrease the energy consumption by the main fans. Consequently, it decreases the costs of mine ventilation. The research was carried out on the basis of ventilation network under assumption constant air density.

2. Forced airflow in a mine

To keep sufficient amounts of air in excavations is to compute and obtain the forced airflow (Madeja-Strumińska & Strumiński, 2004a; 2004b; Kolarczyk, 1993). This issue is also named as the regulation of the ventilation network. The known values are: the structure of the network, air resistance of the branches and assured „a priori" air quantity in selected branches. The unknown values are: fan pressure and air quantity of the main fans, quantity of airflow in the other branches, position and setting of the regulator. These regulators can be the stoppings or auxiliary fans. In ventilation networks with variable air density the heat and mass exchange between the airflow and the vicinity should be also taken into consideration (Dziurzyński & Kruczkowski, 2007; Dziurzyński & Krawczyk, 2012). In the mining ventilation networks the branches with dependent air streams may exist (Kolarczyk, 1993) and these air currents are diagonal (Krach, 2014). Branches with dependent air streams may exist in the area of intake and return air. Among the branches with dependent return air streams there are also the cross-system air streams branches which combine the subnetworks of the main fan. The considerations about the influence of connection of subnetworks of main fans on stability of their work were presented in a cited book (Pawiński et al., 1979). However, this is different problem than presented in the article, but it deals with a similar ventilation system which includes branches connecting the sub-networks of main fans. These branches are essential because of the fact that there are a lot of possibilities of returning air from excavations and chambers to the exhaust shafts. According to them it can be kept larger or smaller amounts of air to particular return shafts.

When restructuring of the mining sector mines is commonly based on their connecting thus, ventilation networks which are created include the branches with air streams mentioned above.

It is not a problem to calculate the forced airflow within the ventilation networks having single main fan. In these cases the unknown number of values is higher by one than the number of equations based on the first and the second Kirchoff's laws for ventilation networks. There is well known method (developed in 1930 year) (Sałustowicz, 1930a; 1930b; 1931) which uses the critical path. This method enable to determine the resistance of stoppings or needed fan pressure of auxiliary fans which makes the output power of the main fan as the lowest. In this method on the critical path there is a regulator, for example: the stopping with air resistance equals zero or an auxiliary fan with fan pressure equals zero as well. Such a performance causes the decrease of unknown values about 1. As a result the equality of number of equations with the number of unknown values. That system of equation has only one solution hence there is the only one airflow in the zones of intake and return air. In ventilation networks where there are more main fans which subnetworks are not connected to another in the area of return air, the way of performance is alike (Sałustowicz, 1931). The difference is that the number of critical paths increase which equals the number of main fans. In cases where subnetworks of main ventilation fans are connected by diagonal branches with subsidiary currents, the mentioned methods cannot be applied. It is necessary to employ a new method.

Assuming that the number of branches in a ventilation network is m, the number of nodes is n, the number of air exhaust lines (with imposed airflow volume) is l, and the number of fans is w, we arrive at:

- as for Kirchhoff's first law: $n - 1$ equations,
- as for Kirchhoff's second law: $m - n + 1$ equations (McPherson, 1993).

Therefore the total number of equations is equaled to m. The unknowns include the required fan pressures in the w number, the airflow volume in branches in the $m - l$ number and regulators' setpoints in the l number. The total number of unknowns is therefore equal to $w + m$ and is higher than the number of equations.

In a ventilation network with two fans, the number of unknowns will equal to $2 + m$ and it will be greater by two than the number of equations as for Kirchhoff's laws. Even the setting up of a regulator with a zero setpoint on the critical ventilation path does not equalize the number of equations with the number of unknowns. Therefore, in networks with two main ventilation fans with connected subnetworks, the number of unknowns will be higher by one than the number of equations – that indicates the possibility of obtaining an infinite number of results differing in air distribution, regulators setpoints and parameters of main fans. This is consistent with a previous observation that in networks of this type it is possible to direct the airflow between various return shafts. 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).

3. Methodology of identification of the optimal forced air distribution in networks with cross-system current

Due to economic reasons, it is beneficial to identify the forced air distribution with the lowest total output power of fans. The air distribution may be treated as optimal in terms of energy output.

In networks with cross-system currents, the use of Sałustowicz's method does not lead to the achievement of an optimal air distribution. Thus, it is necessary to use a new computing method. The method consists of the following algorithm steps:

1) Assumption of airflow rate in a branch with a fan.
2) Determination of air distribution in the ventilation network (e.g. with the Hardy-Cross method) that is consistent with Kirchhoff's laws. Such air distribution includes the airflow rate assumed in step 1) of the algorithm.
3) Determination of the required main fans pressure on the basis of the pressure decrease on the critical path.
4) Determination of regulators setpoints (stoppings resistances and/or fans pressure of auxiliary fans) on the basis of equations resulting from Kirchhoff's 2nd law for external cycles (passing through the branch symbolizing the atmosphere).
   Subsequently, the assumed value of airflow rate in the branch with a fan is changed and steps 1-4 are repeated. This results in a set of solutions characterized by various air distributions, regulators setpoints, and parameters of fans.
5) Resulting dependencies: required fan pressure and output power from set airflow rate in the branch with a fan. Obtaining those results is possible due to the fact that each of the previously obtained solutions differs in the values of required fan pressures and assumed airflow rate in the branch with a fan.
6) Determination of dependency connecting the total power output of the main ventilation fans from the set airflow rate in the branch with a fan.
7) Determination of first derivative of the function obtained in step 6) of the algorithm and equating it to zero. The result is the value of airflow rate in the branch with a fan, for which the air distribution will be characterized by the lowest total output power of the fans.
8) Repetition of steps 2-4 of the algorithm with the use of the airflow value obtained in step 7). The air distribution will be optimal (and therefore the most beneficial when it comes to energy consumption required to ventilate the mine) in terms of minimization of the fans' output power for such values of the regulators setpoints and fan parameters.

4. Case study

Figure 1 shows the three-dimensional output schematic of the mine. The mine has one intake shaft and two return shafts with the main ventilation fans W1 and W2. The mine consists of five mining divisions, designated as A, B, C, D, and E. The air is distributed to them by the intake shaft (branches 1-2 and 2-3 – as per the numeration of nodes), and exhausted through the return shafts (branches 15-17 and 16-18) to the fans W1 and W2 respectively. The unique feature of this network is the connection between return shafts – branches 14-15, 14-12, 12-13, and 13-16. These branches create a string of subnetworks of the fans W1 and W2, so their air currents act in a cross-system manner. These branches make it possible to direct the exhaust air from mining areas between the fan W1 and the fan W2. This is achieved by regulating devices, which should be located – in accordance with the Polish law – in the intakes of the mining areas.

The node 100 represents the external atmosphere. The branches 19-100, 20-100, 100-1, marked with a dotted line, represent the atmosphere and their aerodynamic resistance is equal to 0.

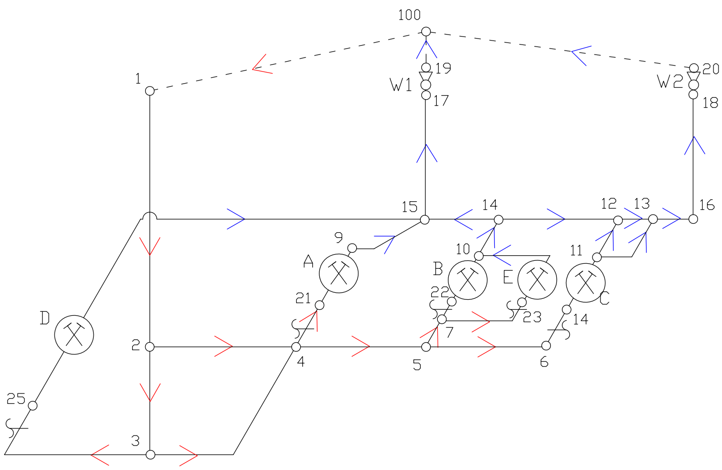

Fig. 1. The three-dimensional output schematic of mine A (own work)

The three-dimensional output schematic (Fig. 1) is a basis for the canonical diagram (Fig. 2). The green dotted line marked as "TI" designates the total cross-section passing through the branches with the air exhaust lines (through the mining areas). This cross-section divides the ventilation network into 2 parts: intake air area – below the cross-section line; and return air area – above the cross-section line.

The ventilation network shown in Figure 2 consists of 25 nodes and 32 branches (Table 1). The cyclomatic number (Wilson, 2017) for this network is 8. Therefore, it is possible to formulate 24 equations resulting from Kirchhoff's first law for nodes, and 8 equations on the basis of

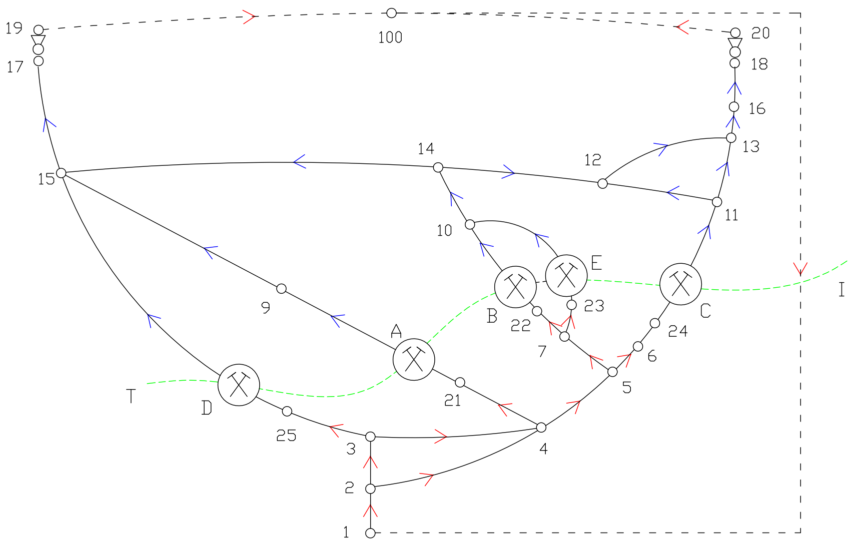

Fig. 2. Canonical diagram of mine A (own work)

Kirchhoff's second law for cycles. The total number of equations is thus 32. The unknowns are: airflow rate in 27 branches, setpoints of 5 regulators and the required fan pressure of two fans, which amounts to 34 unknowns. This points to the existence of an infinite number of solutions that meet the requirements of forced distribution. Each of these solutions will differ in air distribution, regulators setpoints, and fans output power. The quantity of air of the main fans are the boundary conditions. Their range varies from 0 m^3/s to a value equal to the total airflow rate in the total cross-section.

Table 1 shows the features of the branches included in the analyzed ventilation network (Fig. 2).

TABLE 1

Features of branches – example 1 (own work)

Branches – numbered by nodes	**Aerodynamic resistance [kg/m⁷]**	**Imposed air quantity [m³/s]**	**Remarks**
1-2	0.1	—	Intake air zone
2-3	0.05	—	Intake air zone
2-4	0.12	—	Intake air zone
3-4	0.1	—	Intake air zone
4-5	0.18	—	Intake air zone
5-7	0.07	—	Intake air zone
5-6	0.12	—	Intake air zone
6-24	0	—	Regulator
24-11	0.45	30	Working area C
3-25	0	—	Regulator
25-15	0.15	30	Working area D
4-21	0	—	Regulator
21-9	0.3	20	Working area A
7-22	0	—	Regulator
22-10	0.5	10	Working area B
7-23	0	—	Regulator
23-10	0.7	10	Working area E
9-15	0.05	—	Return air zone
10-14	0.03	—	Return air zone
11-12	0.09	—	Return air zone
11-13	0.45	—	Return air zone
12-13	0.075	—	Return air zone
12-14	0.13	—	Return air zone
13-16	0.05	—	Return air zone
14-15	0.1	—	Return air zone
15-17	0.15	—	Return air zone
16-18	0.05	—	Return air zone
17-19	0	—	Ventilator W1
18-20	0	—	Ventilator W2
19-100	0	—	Atmosphere
20-100	0	—	Atmosphere
100-1	0	—	Atmosphere

4.1. Optimization of forced air distribution – positive regulation

In accordance to the algorithm presented in chapter 3, an airflow rate has been assumed in the branch with the W1 fan. With the use of "WK" computer software (relying on the Hardy-Cross method), air distribution on individual branches had been determined, taking the previous

TABLE 2

Results of forced air distribution calculations in ventilation network of mine A – variant of airflow quantity of the fan W1 – 40 m^3/s, positive regulation (own work)

Branch number	Branch nodes		Resist. (g/m^7)	Airflowrate (m^3/min)	Airflowrate (m^3/s)	Dissip. (Pa)	Depr. (Pa)
1	3	25	870.610	1800.00	30.0000	783.549	0.000
2	25	15	150.000	1800.00	30.0000	135.000	0.000
3	4	21	1772.520	1200.00	20.0000	709.008	0.000
4	21	9	300.000	1200.00	20.0000	120.000	0.000
5	7	22	3190.070	600.00	10.0000	319.007	0.000
6	22	10	500.000	600.00	10.0000	50.000	0.000
7	7	23	2990.070	600.00	10.0000	299.007	0.000
8	23	10	700.000	600.00	10.0000	70.000	0.000
9	6	24	0.000	1800.00	30.0000	0.000	0.000
10	24	11	450.000	1800.00	30.0000	405.000	0.000
11	1	2	100.000	6000.00	100.0000	1000.000	0.000
12	2	3	50.000	3382.24	56.3706	158.882	0.000
13	2	4	120.000	2617.76	43.6294	228.423	0.000
14	3	4	100.000	1582.24	26.3706	69.541	0.000
15	4	5	180.000	3000.00	50.0000	450.000	0.000
16	5	7	70.000	1200.00	20.0000	28.000	0.000
17	5	6	120.000	1800.00	30.0000	108.000	0.000
18	9	15	50.000	1200.00	20.0000	20.000	0.000
19	10	14	30.000	1200.00	20.0000	12.000	0.000
20	11	12	90.000	721.31	12.0219	13.007	0.000
21	11	13	450.000	1078.69	17.9781	145.445	0.000
22	12	13	75.000	2521.31	42.0219	132.438	0.000
23	12	14	130.000	–1800.00	–30.0000	–117.000	0.000
24	13	16	50.000	3600.00	60.0000	180.000	0.000
25	14	15	100.000	–600.00	–10.0000	–10.000	0.000
26	15	17	150.000	2400.00	40.0000	240.000	0.000
27	16	18	50.000	3600.00	60.0000	180.000	0.000
28	*17*	*19*	*0.000*	*2400.00*	*40.0000*	*0.000*	*2317.430*
29	*18*	*20*	*0.000*	*3600.00*	*60.0000*	*0.000*	*2696.868*
30	19	100	0.000	2400.00	40.0000	0.000	0.000
31	20	100	0.000	3600.00	60.0000	0.000	0.000
32	100	1	0.000	6000.00	100.0000	0.000	0.000

condition into account. Next, the required fan pressures and stoppings resistances have been designated. Table 2 shows the results of computing assuming the airflow rate in the branch with the fan W1 equal 40 m^3/s.

Bolded font in Table 2 indicates a branch with stoppings (branch resistance is equal to stopping resistance), while italicized font indicates a branch with main fans and the required fan pressure of these fans. Negative values of airflow rate indicate that its direction is reversed in relation to the assumed direction (e.g. negative value in branch 12-14 indicates that the air flows from node 14 to node 12).

The path passing through region C (Fig. 2) turned out to be the critical path; the stopping in the branch 6-24 has a resistance equal to 0. On the basis of the fans' parameters (Table 2) it is possible to calculate their output power. It is equal to: for the fan W1 – 92 697 W, and for the fan W2 – 161 812 W. The total output power of the both fans is therefore 254 509 W.

Next, the algorithm steps 1 – 4 were repeated for various airflows for the fan W1. It was observed that air distribution in the intake air area was identical in each analyzed variant, while there were some variations in the distribution in the return air area. The most important results are presented in Table 3 and shown visually in Figures 3, 4.

TABLE 3

Variant results of forced air distribution in ventilation network of the mine A – positive regulation (own work)

Airflow rate of the fan W1 Imposed values [m^3/s]	**Required fan pressure – W1 [Pa]**	**Output power of the fan W1 [kW]**	**Airflow rate of the fan W2 [m^3/s]**	**Required fan pressure – W2 [Pa]**	**Output power of the fan W2 [kW]**	**Total output power of the fans [kW]**
0	1583.426	0	100	3803.580	380.358	380.358
10	1643.423	16.434	90	3372.362	303.512	319.946
20	1840.43	36.808	80	3076.309	246.104	282.913
30	2086.375	62.591	70	2872.397	201.067	263.659
40	2317.43	92.697	60	2696.868	161.812	254.509
50	2533.336	126.666	50	2549.586	127.479	254.146
60	2753.687	165.221	40	2430.372	97.214	262.436
70	2997.846	209.849	30	2339.032	70.170	280.020
80	3290.808	263.264	20	2275.469	45.509	308.774
90	3657.084	329.137	10	2240.124	22.401	351.538
100	4098.933	409.893	0	2226.146	0	409.893

By analyzing Figure 3, it can be observed that along with the increase of set airflow on the fan W1, the required fan pressure of that fan also increases, while the required fan pressure of the fan W2 decreases. It must be noted that even when directing the entirety of air flowing through the mining areas to the fan W1, the fan pressure of the fan W2 (2226 Pa) is necessary. The same conclusion must be drawn while directing the air on the fan W2 – the required fan pressure of the fan W1 is equal to 1583 Pa.

The increase of airflow on the fan W1 results in a rise in the output power of this fan and a decrease in output power of the fan W2 (Fig. 4). It can also be said that the function of total output power of the fans W1 and W2, and airflow on the fan W1 is a convex function and its

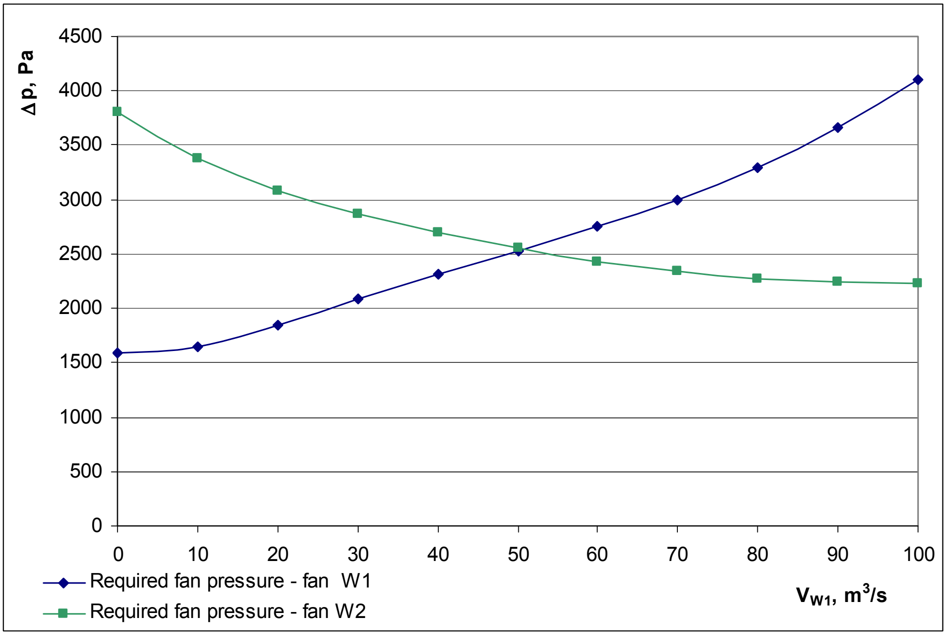

Fig. 3. Required fan pressure of the fans W1 and W2, depending on the assumed value of airflow rate of the fan W1 – positive regulation (own work)

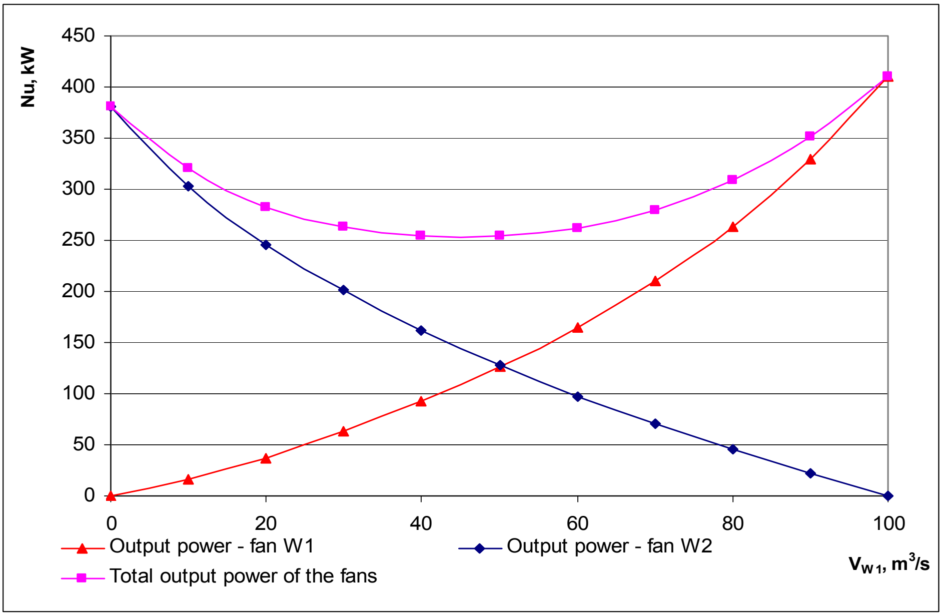

Fig. 4. Output power of the fans W1 and W2, and the sum of their power depending on the assumed value of airflow rate of the fan W1 – positive regulation (own work)

minimal value is located in the analyzed range. For the purposes of further analysis, it has been interpreted as a polynomial function of the third degree, which is described by the equation (1).

$$N_{u(W1,W2)} = -0.000070 \cdot (V_{w1})^3 + \\ + 0.066832 \cdot (V_{w1})^2 - 5.678205 \cdot (V_{w1}) + 375.411401 \quad (1)$$

which the coefficient of determination R^2 is 0.995.

Knowledge of the above function allowed to determine airflow rate V_{w1}, which allows to achieve the lowest total output power of both fans. Subsequently, the use of this airflow allowed to determine the most efficient forced air distribution in terms of minimizing the total output power of the the fans. For the purposes of analyzed example, the optimal value of airflow rate V_{w1} was 2746.374 m^3/min (45.7729 m^3/s), and its total output power of both fans equaled to 253.311 kW and was lower than the total output power achieved in each variant shown in Table 3. The required fan pressures of fans were: the fan W1 – 2 443.941 Pa, and the fan W2 – 2 608.408 Pa.

The difference of the total value of fans output power between the optimal air distribution (253.311 kW) and the least beneficial (409.893 kW) equaled to 156.582 kW. For these two distributions, the difference in annual energy consumption of the fans was (assuming the fan efficiency of 80%) 1 714 MWh, which was the difference of 245 102 EUR in fans operating expenses (at cost of 1 kWh – 0.143 Euro).

4.2. Optimization of forced air distribution – negative regulation

The initial calculations were similar to the positive regulation computations and the location of the negative regulators (auxiliary fans) were identical to the location of the positive regulators (Fig. 1). The difference was that the regulators setpoints were equal to the fan pressures of auxiliary fans. Table 4 shows the results of computing conducted under the assumption of airflow rate in the branch 17-19 (fan W1) equal to 40 m^3/s.

The bolded font in Table 4 indicates the branches with auxiliary fans (the depression in this branch is equal to the required fan pressure of the auxiliary fan), while the italicized font – a branches with main fans. Under this type of regulation the path passing through region D (Fig. 2) turned out to be the critical path; the required fan pressure of the auxiliary fan in branch 3-25 was equal to 0. An important thing to note is that after assuming an identical airflow rate on fan W1, air distributions to the individual branches under positive and negative regulations did not differ. Airflow rate were the same for each branch under both types of regulation (Table 2 and Table 4). The output power of the fans under negative regulation was: the fan W1 – 61 355.8 W, the fan W2 – 114 799.2. The total output power of both fans is equal to 176 155 W. The values obtained were lower than the respective values of output power obtained under the positive regulation.

Table 5 shows the most important computation results for various airflow rate for the fan W1, while Table 6 shows the calculation results of auxiliary fans' parameters. The airflow rate passing through the auxiliary fans equals to the airflow rate passing through the appropriate mining areas (Tab. 1). Additionally, these results are shown in Figures 5 and 6.

TABLE 4

The computation results of forced air distribution in the ventilation network of the mine A – variant of airflow rate on the fan W1 – 40 m^3/s, negative regulation (own work)

Branch number	Branch nodes		Resist. (g/m^7)	Airflow rate (m3/min)	Airflow rate (m3/s)	Dissip. (Pa)	Depr. (Pa)
1	3	25	0.000	1800.00	30.0000	0.000	0.000
2	25	15	150.000	1800.00	30.0000	135.000	0.000
3	4	21	0.000	1200.00	20.0000	0.000	74.541
4	21	9	300.000	1200.00	20.0000	120.000	0.000
5	7	22	0.000	600.00	10.0000	0.000	464.541
6	22	10	500.000	600.00	10.0000	50.000	0.000
7	7	23	0.000	600.00	10.0000	0.000	484.541
8	23	10	700.000	600.00	10.0000	70.000	0.000
9	6	24	0.000	1800.00	30.0000	0.000	783.548
10	24	11	450.000	1800.00	30.0000	405.000	0.000
11	1	2	100.000	6000.00	100.0000	1000.000	0.000
12	2	3	50.000	3382.24	56.3706	158.882	0.000
13	2	4	120.000	2617.76	43.6294	228.423	0.000
14	3	4	100.000	1582.24	26.3706	69.541	0.000
15	4	5	180.000	3000.00	50.0000	450.000	0.000
16	5	7	70.000	1200.00	20.0000	28.000	0.000
17	5	6	120.000	1800.00	30.0000	108.000	0.000
18	9	15	50.000	1200.00	20.0000	20.000	0.000
19	10	14	30.000	1200.00	20.0000	12.000	0.000
20	11	12	90.000	721.31	12.0219	13.007	0.000
21	11	13	450.000	1078.69	17.9781	145.445	0.000
22	12	13	75.000	2521.31	42.0219	132.438	0.000
23	12	14	130.000	–1800.00	–30.0000	–117.000	0.000
24	13	16	50.000	3600.00	60.0000	180.000	0.000
25	14	15	100.000	–600.00	–10.0000	–10.000	0.000
26	15	17	150.000	2400.00	40.0000	240.000	0.000
27	16	18	50.000	3600.00	60.0000	180.000	0.000
28	*17*	*19*	*0.000*	*2400.00*	*40.0000*	*0.000*	*1533.882*
29	*18*	*20*	*0.000*	*3600.00*	*60.0000*	*0.000*	*1913.320*
30	19	100	0.000	2400.00	40.0000	0.000	0.000
31	20	100	0.000	3600.00	60.0000	0.000	0.000
32	100	1	0.000	6000.00	100.0000	0.000	0.000

The analysis of required fan pressure of the fans W1 and W2 (Fig. 5) as well as of the output power of every fan (Fig. 6) leads to a conclusion similar as in the case of positive regulation (Fig. 3 and 4). The approximation function (including the output power of auxiliary fans) takes the following (2) form for negative regulation with the coefficient of determination R^2 equal to 0.999.

$$N_{u(W1,W2,\ Wpom)} = -0.000082 \cdot (V_{w1})^3 + \\ +0.06987 \cdot (V_{w1})^2 - 6.44451 \cdot (V_{w1}) + 361.18249 \quad (2)$$

TABLE 5

Variant calculation results of forced air distribution in ventilation network of the mine A – negative regulation (own work)

Airflow rate of the fan W1 Imposed values [m³/s]	Required fan pressure – W1 [Pa]	Output power fan W1 [kW]	Airflow rate of the fan W2 [m³/s]	Required fan pressure – W2 [Pa]	Output power of the fan W2 [kW]	Total output power of the fans [kW]
0	1293,882	0	100	3559,039	355,903	355,903
10	1308,882	13,088	90	3037,821	273,403	286,492
20	1353,883	27,077	80	2589,762	207,181	234,258
30	1428,883	42,866	70	2214,905	155,043	197,909
40	1533,882	61,355	60	1913,32	114,799	176,154
50	1668,882	83,444	50	1685,132	84,256	167,700
60	1833,882	110,032	40	1510,567	60,422	170,455
70	2028,882	142,021	30	1370,068	41,102	183,123
80	2253,882	180,310	20	1238,543	24,770	205,081
90	2508,882	225,799	10	1091,922	10,919	236,718
100	2793,882	279,388	0	921,095	0	279,388

TABLE 6

Required parameters of auxiliary fans in ventilation network of the mine A (own work)

Required fan pressure – auxiliary fan in area A [Pa]	Required fan pressure – auxiliary fan in area B [Pa]	Required fan pressure – auxiliary fan in area C [Pa]	Required fan pressure – auxiliary fan in area D [Pa]	Required fan pressure – auxiliary fan in area E [Pa]	Total output power of the auxiliary fans [kW]	Total output power of the auxiliary fans and the main fans [kW]
74,541	224,541	10,663	0	244,541	6,501	362,405
74,541	314,541	270,888	0	334,541	16,108	302,601
74,541	384,541	486,547	0	404,541	23,978	258,236
74,54	434,541	657,492	0	454,541	30,106	228,016
74,541	464,541	783,578	0	484,541	34,488	210,643
74,541	474,541	864,454	0	494,541	37,115	204,816
74,541	484,541	919,805	0	504,541	38,975	209,431
74,541	514,541	968,964	0	534,541	41,050	224,174
74,541	564,541	1036,926	0	584,541	44,089	249,170
74,541	634,541	1148,202	0	654,541	48,827	285,546
74,541	724,541	1305,051	0	744,541	55,333	334,721

The function described with equation 2 is a convex function and it takes the minimal value for V_{W1} equal to 3037.84 m^3/min (50.6306 m^3/s). The value of total output power of the main and auxiliary fans was equal to 203.359 kW and was lower by ~20% than the minimal power achieved through positive regulation. The required fan pressure of the fans were: fan W1 – 1678.436 Pa, and fan W2 – 1673.076 Pa.

The difference in the total value of fans output power between the optimal air distribution (203.359 kW) and the least beneficial air distribution (362.405 kW) was equal to 159.046 kW.

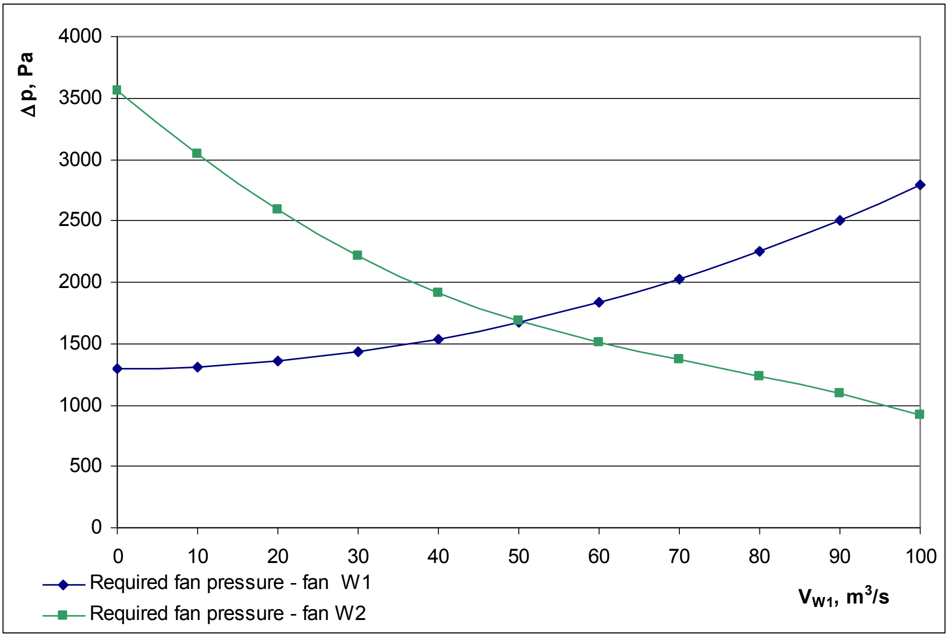

Fig. 5. Required fan pressure of the fans W1 and W2 depending on the assumed airflow rate of the fan W1 – negative regulation (own work)

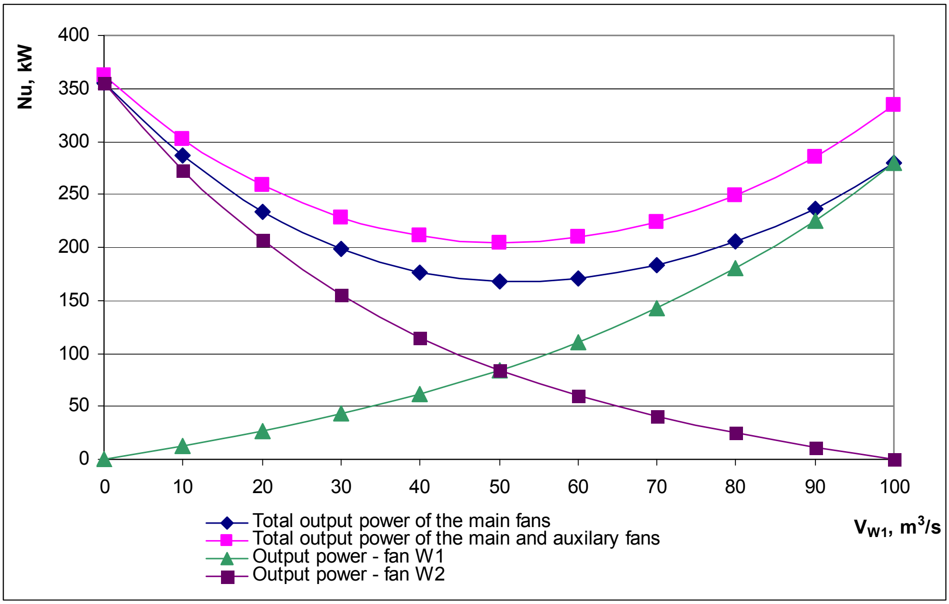

Fig. 6. Output power of the fans W1 and W2, and the sum of their power depending on the assumed value of airflow rate of the fan W1 – negative regulation (own work)

In the case of these two distributions, the difference in annual energy consumption of the fans was (assuming the fan efficiency of 80%) 1742 MWh, which corresponds to the difference of 249 106 EUR in main fans operation (at cost of 1 kWh – 0.143 Euro).

4.3. Comparative analysis of forced air distributions under positive and negative regulations

Analyzing the required fan pressure of the fans W1 and W2 under positive and negative regulations (Fig. 7) it can be concluded that under the positive regulation they are higher in the whole analyzed range of imposed airflow rate on the fan W1. It must be noted that in the case of airflow rate on the fan W1 equal to 0 m^3/s this difference for the fan W1 was 289 Pa, and for the fan W2 244 Pa. With increasing the set airflow through the fan W1 that difference grows, until it approaches identical values for the fans W1 and W2 – 1305 Pa at V_{w1} = 100 m^3/s. Thus, it can be assumed that in the analyzed case increase of airflow rate through the fan W1, makes decreases of the differences between pressure decreases (on stoppings – positive regulation) and fan pressure of the auxiliary fans (negative regulation).

The above observations underline the shape of curves representing the total output power of the main fans W1 and W2 achieved under positive and negative regulations (Fig. 8). The difference between that output power at V_{W1} = 0 m^3/s is 24.5 kW, and at V_{W1} = 100 m^3/s is 130.5 kW. Moreover, the difference of total output power of all fans (including auxiliary fans) is respec-

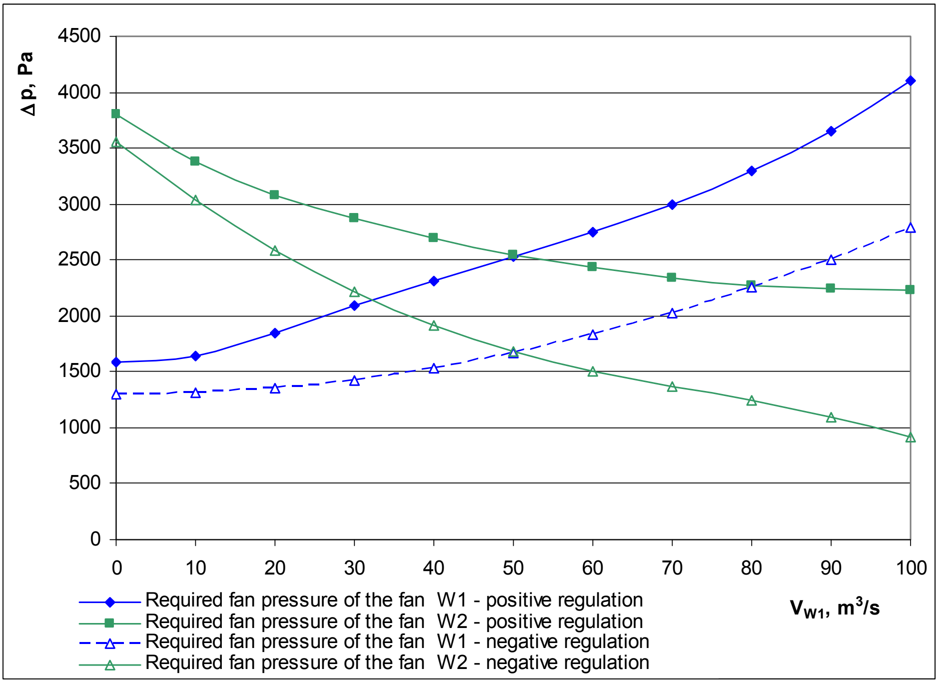

Fig. 7. Comparison of required fan pressure of the fans W1 and W2 under positive regulation and negative regulation (own work)

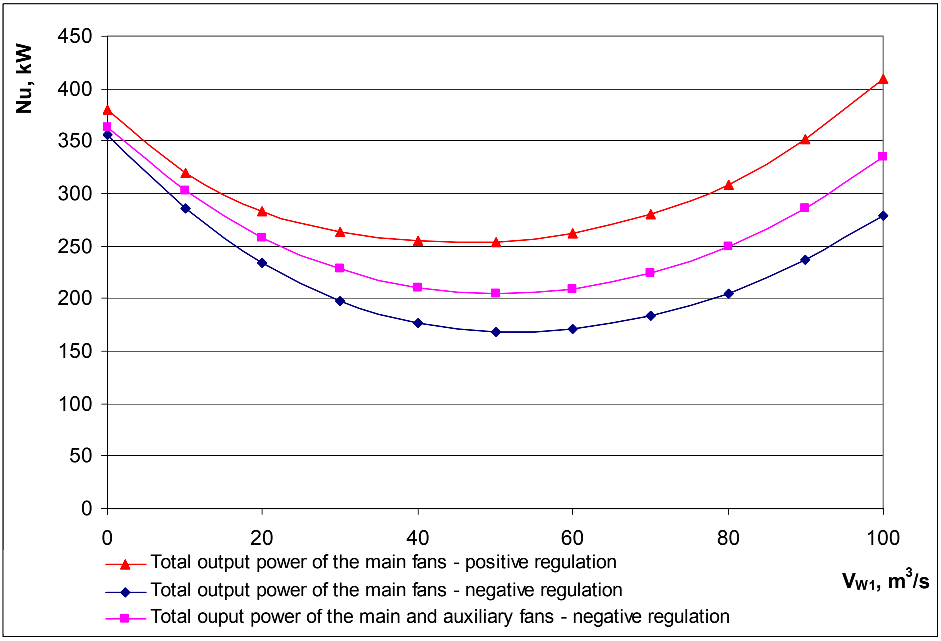

Fig. 8. Comparison of total output power of the fans W1 and W2 under positive regulation and negative regulation (own work)

tively: at $V_{W1} = 0$ m^3/s – 18.2 kW, and at $V_{W1} = 100$ m^3/s – 75.2 kW. The optimal air distribution under positive regulation was achieved at airflow rate on the fan W1 equal to 2746.374 m^3/min (45.7729 m^3/s) – the total output power of the fans was then equal to 253.311 kW, and under negative regulation 3037.84 m^3/min (50.6306 m^3/s) and 203.359 kW, respectively. The difference of total output power between these distributions amounted to 49.952 kW, which corresponds to 547 MWh of annual energy consumption and 78 217 EUR of fans operation expenses (including operation of auxiliary fans under negative regulation).

The curves (Fig. 8) denote the range of total output power of fans achieved through positive and negative regulations, while the area between them (between the upper and middle curves) is indicative of forced air distributions achieved under mixed regulation.

5. Conclusions

Restructuring processes of the mining sector are usually connected with the merging of particular mines. It leads to increase of a number of air currents with return air in a ventilation network. Some of these air currents connect the subnetworks of the main ventilation fans. There are infinite number of air distributions variants in the return air area which meet the ventilation conditions set *a priori*. Each of these variants differs in the fan parameters: fan pressure, airflow rate and output power.

1. The new algorithm presented in this paper allows for determination of optimal air distribution. The air distribution is characterized by the minimal total output power of fans.

2. The algorithm can be used both for positive regulation – by application of stoppings, as well as for negative regulation – by application auxiliary fans.
3. For positive regulation, the difference of total output power of the fans between the optimal air distribution rate and the least beneficial air distribution rate was equal to 156.582 kW, which corresponds to the difference in energy consumption – 1714 MWh and the difference of 245 102 EUR in annual fan operation expenses. Under negative regulation these differences were respectively: total output power of the fans – 159.046 kW, energy consumption 1742 MWh, annual expenses 249 106 EUR.
4. The curves of total output power under positive regulation were located higher at the diagram in relation to the analogous curves for negative regulation in the whole analyzed range of airflow rate through the fan W1 (Fig. 8). This indicates a lower energy consumption under negative regulation. The differences between optimal air distributions under positive and negative regulations were equal to: for total output power 49.952 kW, for annual energy consumption 547 MWh, for annual expenses 78 217 EUR.

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