RESULTS OF MODELLING OF MINE VENTILATION WITH AIR CURTAIN INSTALLED INTO DOWNCAST AND UPCAST SHAFTS

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РЕЗУЛЬТАТЫ МОДЕЛИРОВАНИЯ ПРОЦЕССА ПРОВЕТРИВАНИЯ РУДНИКА ПРИ РАСПОЛОЖЕНИИ ВОЗДУШНОЙ ЗАВЕСЫ В ВОЗДУХОПОДАЮЩЕМ И ВЕНТИЛЯЦИОННОМ СТВОЛАХ

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Key words:
air curtain, main ventilation fan, downcast shafts, upcast shafts, outside air leakage, mine air heater.

Existing mine air heaters (MAH) that heat the air supplied into downcast shafts during the cold period are equipped with a heat channel. A part of the air from a MAH goes through a heat channel. Another part is sucked through a pit head by general depression created by a shaft main fan. That raises a problem of mixing of two air streams, which disturbs thermal regime in the shafts and could lead to violation of safety rules, in particular, create a breach of sealing of intertubular seals. Besides, there is a concern of energy saving during ventilation at underground mining enterprises. One of the reasons for energy efficiency reduce during air supply to a mine are external leaks appeared during ventilation by a suck method.
The article presents proposed solution for both problems using air curtain. During air preparation in the cold period, it is proposed to place air curtain in an air downcast shafts above the junction of a heat channel and a shaft. That is done in order to prevent air infiltration (sucking) through a pit head. According to the paper air curtain should be used in the ventilation shaft to decrease outside air leakage in order to increase energy efficiency of a main fan performance. It is determined during mathematical modelling (in SolidWorks Flow Simulation software) of ventilation and air preparation that air curtain can increase efficiency of MAH and decrease energy consumption on ventilation.

Ключевые слова:
воздушная завеса, главная вентиляторная установка, воздухоподающий ствол, вентиляционный ствол, внешние утечки воздуха, шахтная калориферная установка.

В существующих шахтных калориферных установках (ШКУ), предназначенных для нагрева воздуха, подаваемого в воздухоподающие стволы в холодное время года, используется калориферный канал. Часть воздуха из ШКУ подается по калориферному каналу, а часть подсасывается через надшахтное здание за счет общешахтной депрессии, создаваемой шахтной главной вентиляторной установкой (ГВУ). При этом возникает проблема смешения этих двух потоков воздуха, вследствие чего нарушается тепловой режим в стволах, что может привести к нарушению правил безопасности, в частности к нарушению герметизации межтюбинговых уплотнений. Также на подземных горнодобывающих предприятиях особо остро стоит вопрос энергосбережения при проветривании. Одной из причин снижения энергоэффективности процесса подачи воздуха в рудник является наличие внешних утечек, возникающих при проветривании по всасывающему способу.
В статье приведено предлагаемое решение обеих задач посредством применения воздушной завесы. При осуществлении воздухоподготовки в холодное время года предлагается воздушную завесу размещать в воздухоподающем стволе выше места сопряжения калориферного канала со стволом для препятствия инфильтрации (подсоса) воздуха через надшахтное здание. Воздушную завесу в вентиляционном стволе в настоящей статье предлагается использовать для снижения внешних утечек воздуха с целью повышения энергоэффективности работы ГВУ. В ходе математического моделирования процесса проветривания и подготовки воздуха (в программном пакете SolidWorks Flow Simulation) установлено, что применение воздушной завесы в воздухоподающем стволе позволит повысить эффективность работы ШКУ, а в вентиляционном стволе – снизить затраты электроэнергии на проветривание.

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Introduction

Safety rules [1] prescribe to heat the air sent to the shaft up to the temperature of not lower than +2 °C in the cold season. At that, the whole volume of air entering the shaft across the entire section should have the same temperaure. However, studies conducted in [2, 3] have shown that these rules are not observed in practice. That is caused by the fact that two air streams enter the air-supplying barrel. Those streams are heated in a shaft heater, fed through a calorific channel and sucked through a pit head due to the general shaft depression. Consequently, the air coming from the shaft heater is heated to a much higher temperature than required, which often leads to a significant increase in set air temperature in a shaft. At the same time, there are areas in the air supplying shafts where the air temperature is slightly higher than +2 °C. That indicates low efficiency of the existing method of controlling the air preparation process and the possibility of violation of the temperature regime in a shaft.

An increase in temperature of the air supplied to the mine leads to an increase in energy consumption spent for shaft heater, i.e. to their irrational use [4, 5].

According to the [6], there are from 30 to 50 % of the total electric energy consumed for ventilation by underground mining enterprises. Therefore, development of ways to increase energy efficiency of the main fan is another important task for the industry.

The situation described above, in addition to over-consumption of energy resources during the operation of a shaft heater and deterioration of safety conditions of production, causes an associated problem such as occurrence of the negative general mine natural draft [7-14]. That happens when the warm air injected into the supplying shafts tends to rise upward and cooled air in mine tends to lower down. This problem is relevant for shallow (up to 500 m or less) underground mining enterprises.

Besides, there is a problem characteristic of an inflate method such as occurrence of external air leaks [15], caused by the reason given next. Air is fed through the air supply shafts 1 to the mine by the discharge created by the main fan 2 located on the ventilation shaft 3 (Fig. 1). In addition to the air inflated into the mine, in such a ventilation scheme external air is also sucked into the main fan channel 4 through the mouth of the ventilation

shaft 5, which, when mixed with the total flow, is again discharged into the atmosphere. Therefore, in addition to useful work (fresh air injection), the main fan performs useless work, caused by external air inflation (external leaks).
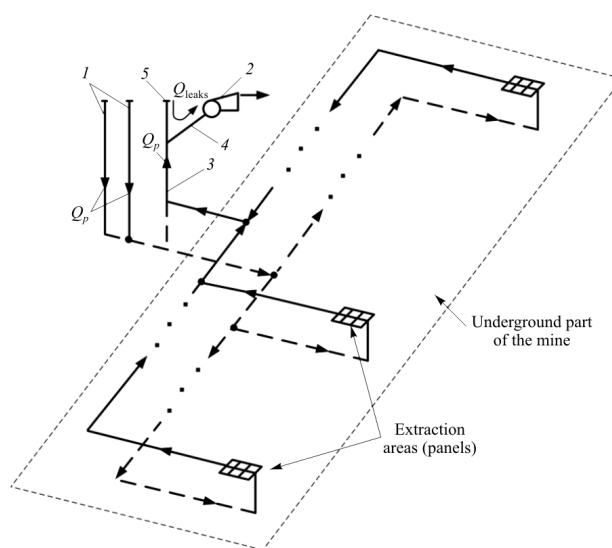

Fig. 1. Simplified scheme of mine ventilation that works on the inflate method

The magnitude of leaks (on example of potash mines), according to [16], is in the range of 9 to 51 %, i.e. there are mines where efficiency of the main fan is only 49 %. In this regard, a reduction of external leaks is one of the main directions in a complex of measures to reduce the costs of mining enterprises for ventilation of underground mining enterprise.

Description of the proposed method of ventilation and air preparation

In order to improve the efficiency of air preparation and reduce the cost of electricity consumed by the main fan, it was proposed in [17] to install an air curtain in the air supply and ventilation shafts (Fig. 2). A curtain in an air supply shaft has to ensure a reduction in the infiltration (suction) of the outside cold air through the overhead building. In this case less energy required for the work of a shaft heater. As a result, it will ensure normalization of the air mixing process in a shaft [18, 19]. An air curtain in the ventilation shaft is necessary to reduce external air leaks [15].

Effectiveness of the process against the external air leaks (suckers) directly depends on the choice of the location of the air curtain in a shaft, parameters of fans that consists it of, and their mutual arrangement.

A double side curtain was previously considered ineffective, because external air leakages in the ventilation shaft decreased slightly [15]. The reason for low efficiency of the air curtain is that the air flows from fans are directed against each other and interfere with each other. In this case, almost no energy remains to counteract external air leaks in the air curtain.
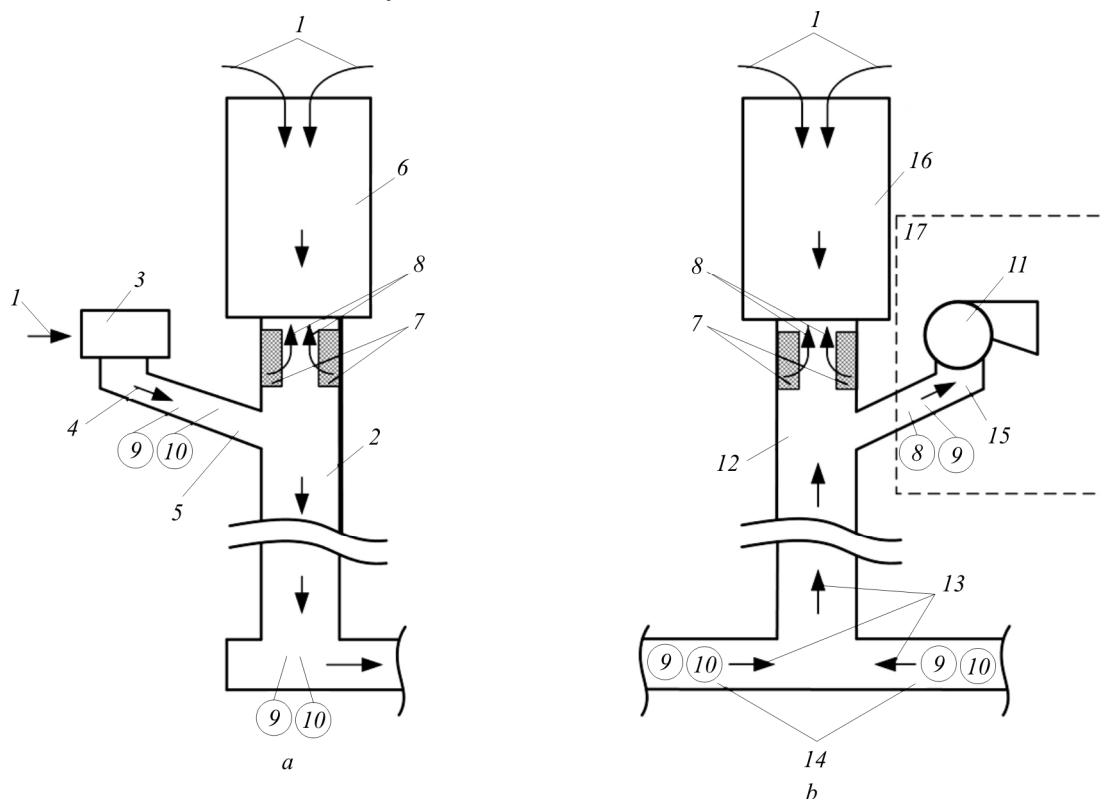

Fig. 2. Ventilation and air preparation according to the proposed method: *a* – air curtain in the air supply shaft; *b* – air curtain in the ventilation shaft: *1* – outside air (cold); *2* – air supplying shaft; *3* – shaft air heater; *4* – heated air; *5* – heater channel; *6* – pit head of air supplying shaft; *7* – air curtain; *8* – air discharged from the air curtain; *9* – the gauge of air rate; *10* – temperature and pressure (or density meter); *11* – main fan; *12* – ventilating shaft; *13* – air passing from the ventilation shaft; *14* – main ventilation excavations; *15* – main fan channel; *16* – pit head of ventilation shaft; *17* – surface complex of the main fan

In order to solve this problem, it was suggested in [20] that the flows of counter-directed fans have to be separated by a partition located in the shaft and the air streams have to be directed at a certain angle α (Fig. 3).

In order to reduce external air leaks through the mouth of the shaft, air curtain fans have to provide the necessary output and pressure. For that, for example, a fan of local ventilation of VME-6 of nonexplosive design can be used. That is used in mines for ventilation of spur excavations. If requested, the fan can be manufactured with a noise silencer.

There are several methods for calculating air curtains based on different approaches [21-24], which for many years remain unchanged. The task of these methods is to determine the speed of the air flow behind the curtain and establish the relationship between the speed and air flow inside that. For example, the velocity in [25] is found by
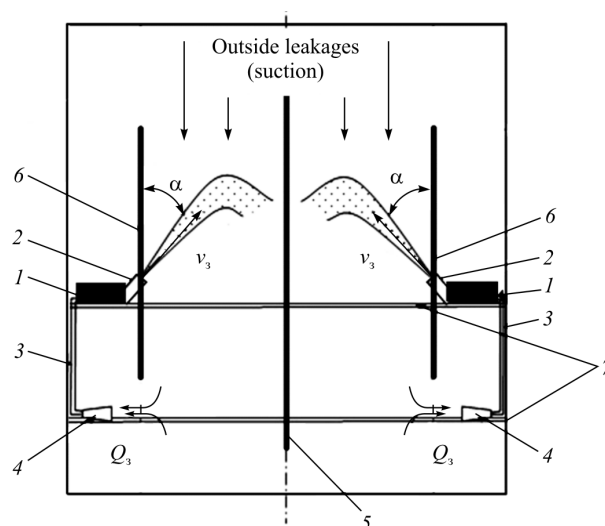

Fig. 3. Principle of the air curtain at the shaft throat: *1* – fans of the curtain; *2* – air suppluing boxes; *3* – pipelines (air ducts); *4* – intake of air; *5* – longitudinal partition; *6* – longitudinal partitions (along the perimeter of the section in the light); *7* – level of armour shaft

adding the velocities of the air and flow jet that hits the curtain. The law of conservation of momentum is used in [24]. At that, usually it is considered that the velocity of the air flow entering the curtain is known [24-27].

Next, the required capacity and pressure of the fan installed on each half of the air curtain are calculated.

The procedure for calculating the parameters of air curtain fans

Initially, when determining the parameters of the air curtain, it is necessary to set the following initial data that is as follows:

1. The cross-section of the shaft at the installation site of a curtain (clear cross-section of the shaft) S_{shaft}, m^2.

2. Average speed of the air flow without regards to the action of the air curtain v_0 and required in respect to its action v_1, m/s.

3. Length of a shaft section L_{shaft} that fans of the air curtain are installed on.

Value of mine ventillation pressure drop (Pa) on a shaft section between junction with a main fan channel (a heater channel) and the surface is determined by the formula

$$h_0 = \frac{aP_{shaft}L_{shaft}v_0}{S_{shaft}^2},$$

where a is for a coefficient determining the type of the shaft (cage, skip) [5, 28]; P_{shaft} is for perimetr of the shaft at the installation site of a curtain (clear cross-section of the shaft), m.

Depending on how much external air leakage (suction) it is supposed to be reduced, the value that it is necessary to increase the aerodynamic drag by (N·s^2/m^8) at the shaft section between the junction with a main fan (a heater channel) and the surface is determined.

$$\Delta R_{shaft} = \frac{R_{shaft}\left(Q_0^2 - Q_1^2\right)}{Q_1^2},$$

where R_{shaft} is for aerodynamic resistance of a shaft section between the junction with a main fan (a heater channel) and the surface, N·s^2/m^8 [5, 28], $R_{shaft} = \frac{aP_{shaft}L_{shaft}}{S_{shaft}^3}$; Q_0 is for volume rate of external air leakages (suction) in case of no air curtain, m^3/s, $Q_0 = v_0 S_{shaft}$; Q_1 is for volume rate of

external air leakages (suction) at the required air speed (v_1) on current section, m^3/s, $Q_1 = v_1 S_{shaft}$.

The required air velocity (m/s) outlet from the air curtain fan slot is determined by the formula

$$v_{a.c} = \sqrt{\frac{G_2 v_2}{2\rho_{a.c}S_s}} = \sqrt{\frac{(G_0 v_0 - G_1 v_1)}{2\left(0,465 P_{a.c}/(273,15 + t_{a.c})\right)S_s}},$$

where G_i is for the air mass flow rate at the i-th point, kg/s, $G_i = Q_i\rho_i$; G_0, G_1 and G_2 are for mass flow rate of external air leakages (suction), with no action of the air curtain, with its action and outgoing from the air curtain, kg/s; S_s is for the surface of a slot of the air curtain fan through which the air flow is discharged; $\rho_{a.c}$, $P_{a.c}$, $t_{a.c}$ and $v_{a.c}$ are for density (kg/m^3), pressure (mmHg) and temperature (ºC) of the air, outlet from the air curtain, and its speed (m/s).

In the case when temperature and air pressure can not be determined, air density is assumed equal to 1,2 kg/m^3.

Performance of the air curtain is regulated by changing the area of the slot of S_s and/or by changing the air discharge angle from its fans. A frequency-controlled fan control drive can also be used.

Results of simulation of the air preparation process using the air curtain in the air supply shaft

Prior to the use of an air curtain in an air supply shaft, it is necessary to determine the effectiveness of the proposed method, for which the SolidWorks Flow Simulation software used for mathematical modelling of air curtain effect on the ventilation and air preparation process was performed in the package [29].

The Fig. 4 shows the results of modeling the processes of air preparation according to the method adopted currently (Fig. 4a) and using the air curtain (Fig. 4b).

As it seen from the figure, the proposed method allows to solve the previously mentioned problems arising during air preparation.

There are no zones with a temperature close to +2 °C in the air supply shaft when using an air curtain. That means the threat of violation of safety rules is eliminated. At the same time, a shaft heater will require a smaller amount of energy resources, i.e. cost of air preparation will be reduce. In comparison with the volume of energy resources

used for operation of a shaft heater, the costs of electric power used to operate the air curtain are incommensurably small.
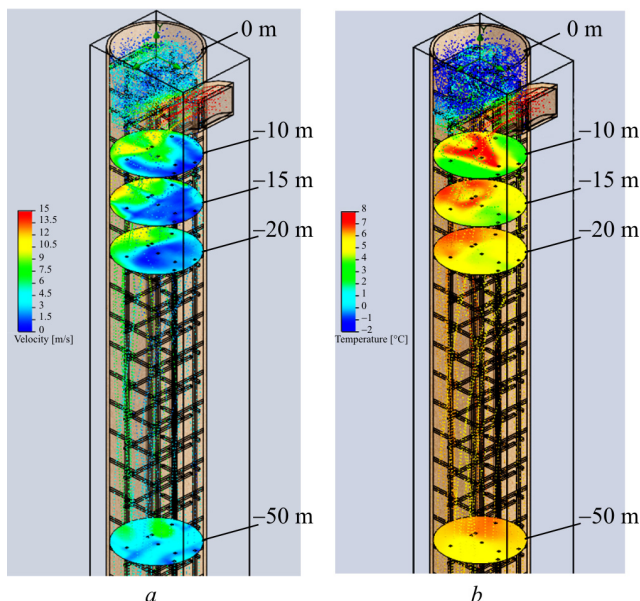

Fig. 4. Distribution of air temperature along the cross-section of the air supplying shaft at different depths by mixing cold and warm air using an air curtain installed at the shaft throat: cold air –20 °C (20 m³/s), warm air +8 °C (147 m³/s): *a* – with no air curtain in the air supply shaft; *b* – air curtain in the ventilation shaft

Air heated unifirmly will reduce the overall value of air temperature throughout the section of the air supply shaft. In that case, either negative temperature drops between the shafts will be decreases or their direction will be reversed (positive temperature drops). Reducing the volume of air supplied to the mine will lead to the fact that the operating mode of the main fan will need to be transferred to the area of higher pressures. Under the action of positive natural draft, on contrary, a greater volume of air will be supplied to the mine. That means the operating mode of the main fan can be switched to the lower pressure range.

There is a similar situation occure when adjusting for the reason described next. In case there is no general mine natural draft (general mine temperature drop), curve of mine characteristics occupies a certain position 1 (Fig. 5). At that, the main fan should provide an air supply Q_1. An operating mode of the main fan is in this case is chosen according to the operating point (the point of intersection of the curves of mine characteristics and fan characteristics) that falls into the area of maximum efficiency.

The change in the absolute value of general natural draft will lead to the change in position of the curve of the mine to a certain position 2 (with a negative general natural draft on the Fig. 5*a*, with a positive general natural draft on the Fig. 5*b*).

Switching of the fan to another characteristic will result to the change in its performance: with negative natural general mine draft impact ($-h_e$) 0° (see. Fig. 5*a*); with positive natura general mine draft impact ($+h_e$) –10° (see. Fig. 5*b*). At such a regulation, an amount of air Q_2 will be supplied to
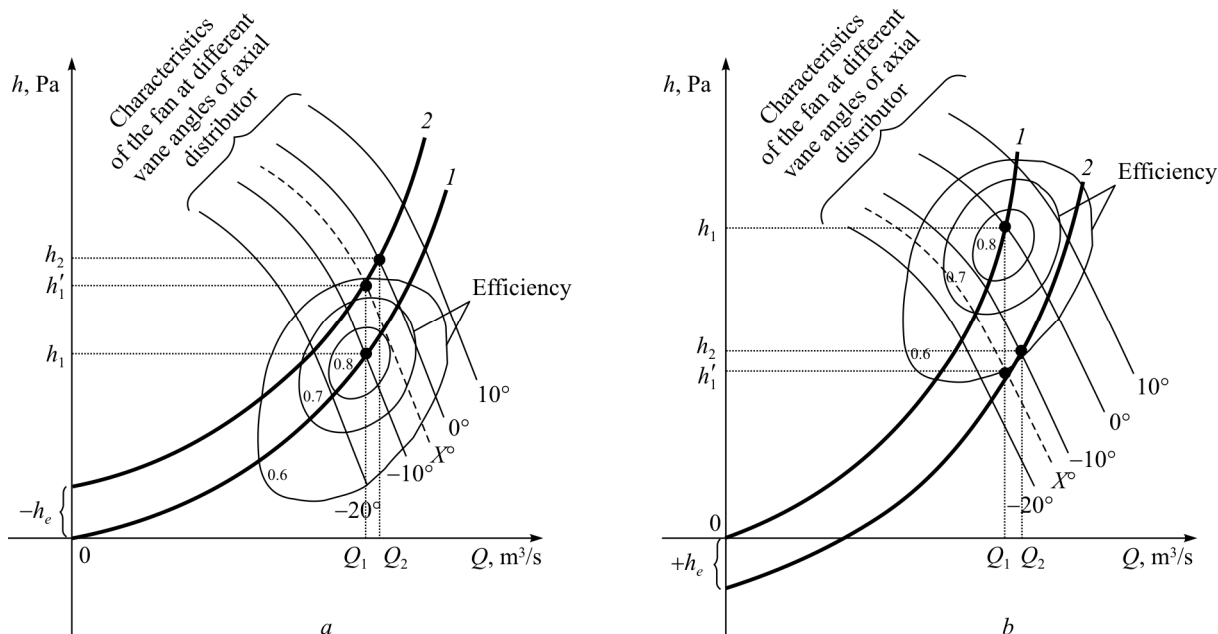

Fig. 5. Change in a position of the curve of mine characteristics: *a* – under the action of negative general mine natural draft; *b* – under the action of a positive general mine natural draft

the mine more than the required Q_1, which entails additional energy costs. To avoid additional costs of electricity is possible by adjusting the angle of installation of an axial distributor to a certain position X^0 (see Fig. 5). However, in terms of execution it is quite difficult. Taking into account the fact that the general mine natural draft changes constantly and fairly within a wide range [12], it can give an error when adjusting the angle of installation of axial distributor's blades. In addition, switching of the fan to another operating characteristic will inevitably decrease the efficiency (see Fig. 5). Due to that, an axial distributor will consume more electricity.

Changes in performance of the main fan can be achieved by adjusting the rotational speed of a fan impeller. For that an adjustable electric drive can be used. Performance of an electric drive will maintain required capacity due to speed and current feedback [30]. In this case, a drive control system will be adjusted so that the fan operates at the maximum efficiency. However, such regulation ensure overall natural draft that will have a significant impact on the operation of the main fan.

Results of simulation
of the ventilation process with the air
curtain in the ventilation shaft

During the mathematical modeling of the operation of the air curtain in the ventilation shaft (Fig. 6), it was established that under the accepted conditions external air leakages will be decreased from

60.43 to 26.27 m³/s (by 43.5 %), and 444.36 m³/s will be needed for performance of the main fan instead of 409,46 m³/s.

Due to the change in a structure of air flow in the region of air curtain two recirculation circuits are created. Circuits provide additional aerodynamic resistance at the throat of ventilation shaft from zero to the junction with the ventilation channel, thereby reducing the amount of external leaks. In this case, the shaft ensures maximum efficiency of the air curtain.

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– amount of air supplied to the mine should not be less than the estimated amount of air required for airing the mine;

– cost of an air curtain should not exceed the cost of the main fan for external air leakages;

– cost of one cubic meter of fresh air supplied to the mine should be minimal.

The Fig. 7 shows characteristics of the main fan, characteristics of the mine network, operating points without the action of the air curtain (operating point A) and with the reduction of surface leakages with the air curtain (operating point C).
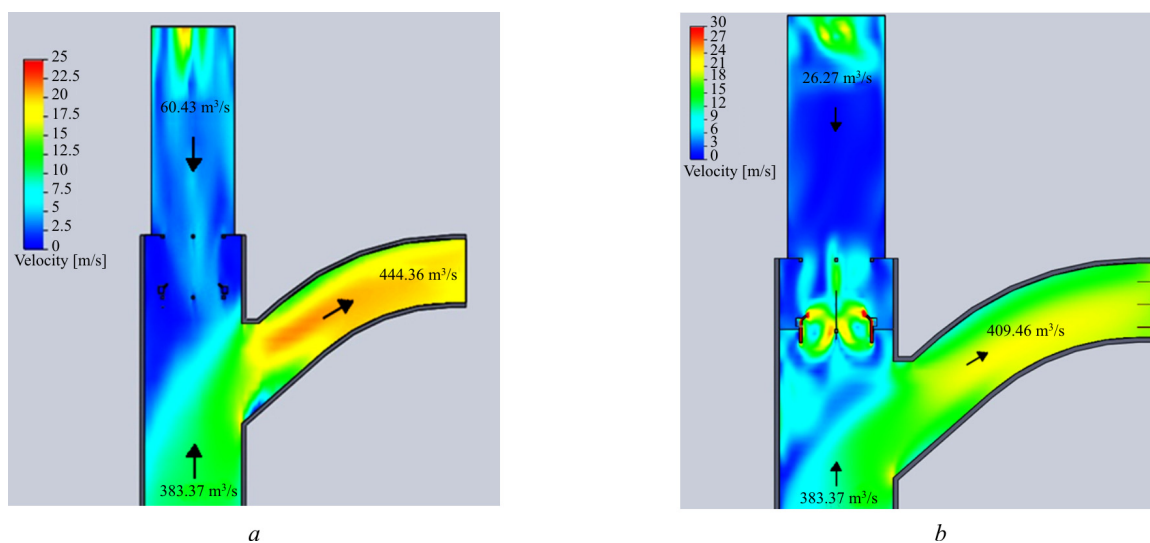

Fig. 6. Result of mathematical modeling of the distribution of air flows in the ventilation shaft:
a – with no air curtain in the air supply shaft; *b* – with an air curtain in the ventilation shaft
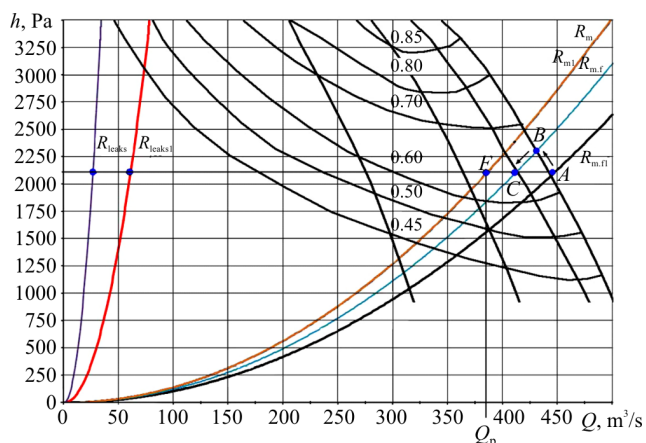
Fig. 7. Aerodynamic characteristics: R_{leaks1} is for aerodynamic resistance of external leakages of the air before the installation of air curtain; R_{leaks} is for aerodynamic resistance of external leakages of the air after the installation of air curtain; $R_{m.f1}$ is for aerodynamic resistance of the ventilation network before instalation of the air curtain; $R_{m.f}$ is for aerodynamic resistance of the ventilation network after instalation of the air curtain; R_m, R_{m1} are for aerodynamic resistance of the mine before and after instalation of the air curtain; A, B, C are for fan operating points for various operating modes; F is for the amount of fresh air entering the mine

Several results are obtained by the action of air curtain such as aerodynamic resistance of the shaft section increases from zero to the junction with the ventilation shaft, which increases the aerodynamic resistance of external air leakages from R_{leaks1} to R_{leaks} (see Fig. 7). At the same time, the aerodynamic resistance of the mine R_m, R_{m1} remains the same and the aerodynamic resistance of the ventilation network increases from $R_{m.f1}$ to $R_{m.f}$ which the main fan operates for.

The operating point A of the main fan propeller moves along the aerodynamic characteristic of the fan to the point B. After the movement of the operating point of the the main fan propeller B to point C by changing the angle of installation of the main fan vanes, the amount of fresh air that enters the mine Q_m remains the same (F) and consumed electric power of the main fan decreases.

The amount of electricity (kWh) saved as a result of the air curtain in the ventilation shaft, according to [31], is determined by the formula

$$N_s = \frac{T}{1000\eta_m}\left[\frac{Q_{m.f}h_{m.f}}{\eta_{m.f}} - \frac{Q'_{m.f}h'_{m.f}}{\eta'_{m.f}}\right] - \frac{2TQ_{a.c}\,h_{a.c}}{1000\cdot\eta_{m.c}\,\eta_{a.c}},$$

where T is for the fan operating time per year, h; η_m is for the efficiency of the main fan electric motor, p.u.; $Q_{m.f}$, $h_{m.f}$ are for efficiency of the main fan, m³/s, and its pressure, Pa; $Q_{a.c}$, $h_{a.c}$ are for efficiency of the air curtain propeller, m³/s, and its pressure, Pa; $\eta_{m.c}$ is for efficiency of the electric motor of the air curtain, p.u.; $\eta_{m.c}$ is for the static efficiency of the air curtain propeller, p.u.

For each specific case the value of the saved energy have to be calculated. However, it is obvious that use of the air curtain in the ventilation shaft in order to increase the energy efficiency of ventilation is powerful.

Conclusion

It was established during the mathematical modeling that there is almost uniform heated air observed on its cross section when an air curtain is used for air preparation in an air supplying shaft. At the same time, it is possible to lower the temperature of the outgoing flow from the main fan by reducing the volume of sucked air through the supernumerary building of the air supplying shaft. As a result of that energy costs spent for air preparation is reduced.

By reducing the temperature of air entered the air supply shafts, negative (increasing positive) thermal depressions (general mine natural draft) will decrease between them. As a result, it is possible to reduce the main fan performance.

In addition, reduce in external air leakages allows reducing the productivity of the mine while maintaining the supply of the required air volume in the mine. Decrease in leakages can also be achieved by instalation of the air curtain in the ventilation shaft.

Thus, the proposed method of ventilation will not only allow air preparation in a safe mode, but also reduce energy costs.

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