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CALCULATION OF THE VOLUME OF AIR FOR VENTILATION OF MINING WORKINGS WHEN OPERATING SELF-PROPELLED DIESEL EQUIPMENT

Purpose. Development of methods for determining the required volume of air for airing workings by the factor of exhaust gases from internal combustion engines (ICE).

Methodology. To determine the actual value of the cleaning efficiency (neutralization) of exhaust gases from automotive diesel emissions from engines which meet the environmental standard Tier III, field measurements on the magnitude of the carbon monoxide concentration (CO) and nitrogen oxides (calculated as NO_2) after the catalytic converter were processed; they were conducted in the conditions of the "United Kirov mine" and the Maleevsky, Tishinsky and Dolinny mines of "Kazzinc" LLC (RF).

Findings. The calculation of specific air consumption according to the method developed by the authors has demonstrated that its maximum value for the Tier III environmental standard is achieved when diluting emissions of nitrogen oxides and is equal to 2.86 m^3/min. per hp.

Originality. During the study in the field of exhaust efficiency of gas purification after the neutralizer, the gas-cleaning coefficient was derived and applied in the method for calculating the amount of air. Studies performed in the area of calculating the specific air flow rate by the exhaust dilution factor have shown the possibility of significantly reducing the amount of air supplied to the atmosphere of the mine to dilute harmful impurities to standard values.

Practical value. The calculation of the amount of air according to modern standards of diesel equipment will allow reducing the cost of ventilation of mine workings. This will increase the service life of equipment involved in the ventilation of mine workings, and significantly reduce the capital costs of mining enterprises, which will lead to positive economic effect.

Keywords: *ventilation, exhaust gases, catalytic converter, air consumption, self-propelled diesel equipment, gas cleaning efficiency*

Introduction. The exploitation of self-propelled equipment with internal combustion engines at mining enterprises is accompanied by the release of exhaust gases containing toxic impurities: carbon monoxide, nitrogen oxides, aldehydes, soot, etc. into the mine atmosphere. Ensuring regulatory concentrations of pollutants in the mine air is achieved by supplying the mine workings, where machines with internal combustion engines are operated, with the necessary quantities of fresh air. The volume flow of air per unit of time per hp of the installed engine power Q is usually taken as an indicator for the calculation (m^3/min per hp). The magnitude of this indicator depends on many factors, the main of which is the specific value of emissions of pollutants, determined by the environmental standard of the internal combustion engine, and the efficiency of exhaust gas cleaning.

Table 1 shows standard values of the specific amount of air required for dilution of gases resulting from operation of machines with ICE used in Russia and other countries.

Analysis of the data in this table indicates that the specific air amount required to dilute the gases resulting from the operation of machines with internal combustion engines for different countries varies in a wide range. This may be related to the type of internal combustion engines installed on the machines and the environmental standard (toxicity standard) for which they work, the efficiency of exhaust gas purification, the operating conditions of mining equipment (the speed of self-propelled machines in the mine workings, their actual power, the geometric dimensions of the mine workings and etc.). Higher specific air values refer to the Tier I, II toxicity standards; Stage I, II, IIIA; Euro I-III, and smaller values to the standards of toxicity Tier III, IV; Stage IIIA, IIIB, IV; Euro IV–VI [2].

Currently, "The Safety Rules for Mining and Processing of Solid Minerals" are in effect in Russia, they came into effect on 03.10.2014, regulating the need to ensure that when operating the mine machines with ICE, the oxygen content in the air is at least 20 % (by volume) and the content of harmful impurities in the outgoing jet is below the maximum allowed concentration (MAC) established by the safety rules [3].

To determine the required amount of air for airing workings with the exhaust gas factor from the internal combustion engine, it is necessary to make a reasonable choice regarding air flow, applicable for the specified mining enterprise. It is this reason that has led to the relevance of this study for substantiation of the reduced values of the norms of specific air flow.

Analysis of the problem. The volume of air that must be supplied to the mine workings, where stationary or mobile machines with diesel internal combustion engines are located, depends on many factors. The most important of them is the amount of exhaust emissions and the concentration of harmful substances in them.

The concentration of harmful substances in the exhaust gases is largely dependent on neutralizers, which are introduced into the exhaust system of the engine. There are liquid,

Table 1

The amounts of air required for the dilution of gases resulting from the operation of machines with internal combustion engines [1]

Country	The value of Q_{ICE} per unit of power of machines with internal combustion engines, m^3/min. per hp
Russian Federation (Norilsk MMC, Apatity JSC)	3
Australia	2.6
Canada	2–4
Chile	2.8
China	3
South Africa	2.8
USA	0.44–6.1 (depending on Tier standards for each type of engine)
Germany	3–5
France	2–4
Kazakhstan (Shalkiy mine)	3.5

catalytic, thermal and combined neutralizers. On self-propelled underground machines with diesel engines, mainly combined two-stage gas cleaning system is used, consisting of catalytic and liquid neutralizers [4].

To determine the actual value of the cleaning efficiency (neutralization) of exhaust gases from automotive diesel emissions from engines which meet the environmental standard Tier III, field measurements in terms of the magnitude of the carbon monoxide concentration (CO) and nitrogen oxides (calculated as NO_2) after the catalytic converter were processed, which were conducted in the conditions of the "United Kirov mine" and the Maleevsky, Tishinsky and Dolinny mines of "Kazzinc" LLC.

The effectiveness of catalytic converters, which were used with all units of the equipment under study, was established in the following sequence.

The amount of exhaust gases was established according to the technical documentation for each of the machines with a diesel engine. For this, we used the working volume of cylinders (V_{dv}) and the crankshaft rotational speed (n)

$$q_{og} = 0.5 \cdot V_{dv} \cdot n, \tag{1}$$

where q_{og} is the amount of exhaust gases, m^3/min.

The concentration of carbon monoxide (CO) and nitrogen oxides (in equivalent of NO_2) from the engine was set as the ratio of the specific emission values for each component in accordance with the environmental standard Tier III (2) to the total exhaust gases.

$$C_i = 0.1 \cdot j_i \cdot N_{dv}/60 \cdot \rho_i \cdot q_{og}, \tag{2}$$

where C_i is the concentration of the component, mg/m^3; j_i is the specific value of the emissions of the component, g/kW · h (g/hp · h); N_{dv} is power of the engine, hp; ρ_i is the density of carbon monoxide (ρ_{CO} = 1.15 kg/m^3) and nitrogen oxides ($\rho_{NO_2} = 2.1\,\text{kg}/\text{m}^3$).

The gas cleaning efficiency ratio (K_{ef}) was calculated (3) as the ratio of the component concentration to the measured value of the concentration of each component after the catalytic converter.

$$K_{ef.} = C_i / C_{imeas.}, \tag{3}$$

where $C_{imeas.}$ is the measured value of the concentration of the component, %.

In the subsequent processing of the results, the Kef values greater than 8 for carbon monoxide and 5 for nitrogen oxides were not taken into account.

The results of establishing $K_{ef.}$ after data processing are presented in Figs. 1 and 2.

The results of the analysis show that gas cleaning efficiency is not the same for carbon monoxide as for nitrogen oxides. In the first case, it is equal to 5.1, which corresponds to decrease in carbon monoxide emissions by approximately 80 %. In the second case, it reaches 3.5 and corresponds to decrease in emissions of nitrogen oxides by 71 %.

The data obtained as a result of measurements and calculations can be used to substantiate the air norms for airing the workings in which diesel ICE are used.

The method of calculating the amount of air required for ventilation of mine workings, where self-propelled diesel equipment with ICE is used. In local practice, the required amount of fresh air for static dilution of emissions of pollutants contained in exhaust gases to standard values is calculated by the formula, which differs from the standard by the presence of gas cleaning efficiency factor

$$Q_i = q_{og} \cdot \frac{C_i}{K_{ef.i} C_{mac.i}}, \tag{4}$$

where Q_i is the amount of fresh air for static dilution of emissions of polluting components, m^3/min.

Formula (4) can be easily reduced to a more convenient form for calculations

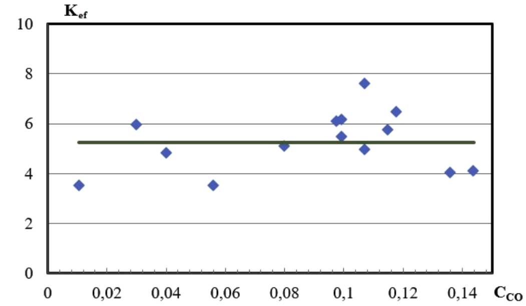

Fig. 1. The ratio of purification efficiency for exhaust gases for carbon monoxide (C_{CO} is the calculated concentration of CO, %)

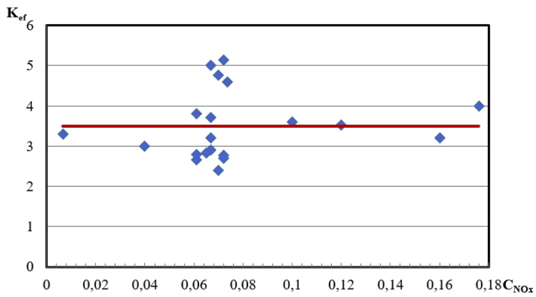

Fig. 2. The ratio of purification efficiency for exhaust gases by nitrogen oxides (C_{NO_x} is the calculated concentration of NO_x, %)

$$Q_i = J_i / K_{ef.MAC.i}, \tag{5}$$

where J_i is total emissions of pollutants contained in the exhaust gases, mg/min.; $J_i = j_i N_{dv}$.

After dividing both parts of the formula (5) by the value of the nominal engine power of the machine N_{dv}, we obtain the value of the specific air flow

$$q_{sp.i} = j_i / K_{ef.MAC.i}, \tag{6}$$

where $q_{ID.i}$ is specific air flow, m^3/min. per hp.

Formulas (4–5) correspond to the case of the so-called static liquefaction of pollutants emitted by the machines, i. e. the case when a self-propelled unit with a diesel ICE is in a stationary state.

The main provisions for calculating the required amount of air to ensure the regulatory (20 %) oxygen content in the air were set forth in an article by the staff of the Ural Branch of State Institute of the Russian Academy of Sciences [5].

The amount of air Q_{O_2} in the oxygen content can be calculated by the formula Q

$$Q_{O_2} = q_{og} C_O / (C_O - 20), \tag{7}$$

where CO is the initial volume concentration of oxygen in the air entering the engine of the machine, %.

In case, if the technical characteristics of the engine of the machine are known, the amount of exhaust gases q_{og} can be calculated by the (1). Otherwise, to calculate q_{Og} we should use the value of fuel consumption $q_{fl.}$ (kg/h per hp) with the maximum engine load and the stoichiometric amount of oxygen l_O (kg/kg) required for complete combustion of the entire amount of diesel fuel. The value of l_O is equal to 3.35 kg/kg. Then the flow rate qog, measured in m^3/min., will be

$$q_{og} = q_{fl.} \cdot l_O \cdot N_{dv}/60 \cdot \rho_{air.} K_O, \tag{8}$$

where $q_{fl.}$ is fuel consumption, kg/h per hp., l_O is stoichiometric amount of oxygen, kg/kg; ρ_{air} is air density, kg/m^3; K_O is the mass content of oxygen in the air, the unit share (the ratio between the mass and volume content of oxygen in the air is 1.105).

Comparison of calculated data, executed by the formulas (1) and (8) for specific types of vehicles with ICE has shown that the difference between the calculated values of q_{og} for specific types of engines, does not exceed 12 %. This confirms the mentioned possibility to calculate q_{oq} using the (1) in the presence of reliable technical characteristics of diesel engines.

The specific amount of exhaust gas is easy to find by dividing the left and right sides of (8) by N_{dv}. In this case, the (7) will show the specific amount of air in m^3/min. required to provide the standard oxygen content

$$q_{O_2} = \frac{0.015 \cdot q_{fl.} \cdot l_0}{\rho_{air} \cdot (C_0 - 20)}. \quad (9)$$

As it was noted before, the dependencies (4–9) make it possible to calculate the amount of air for stationary machines with ICE. In case of movement of a self-propelled machine with ICE, the principle of "dynamic" dilution should be used to calculate the required amount of air. A number of works (S. S. Kobylkina, A. E. Mikheeva, R. A. Udalova, A. S. Kobylkina [6], N. O. Kaledina, S. S. Kobylkin [7]) are devoted to the development of this method.

Using the principle of "dynamic" dilution of harmful gases, the amount of air is calculated by the ratio

$$C_{mac.i} = \frac{J_i}{S_{wor.} V_? \pm Q_i}, \quad (10)$$

where the sign "–" characterizes co-movement of a self-propelled machine and air, and "+" – reverse movement. The preliminary analysis of dependency (10) showed that the highest concentrations of pollutants will occur when the vehicle and air co-move. Thus, we will focus on the analysis of this case.

When the NO_x emission value complies with the Tier III environmental standard, the gas cleaning efficiency is 3.5 and the engine power of the machine is 252 hp, the specific amount of air to ensure $C_{mac.NO_2} = 5\,\text{mg/m}^3$ when the machine with ICE is stationary is $q_i = 50/3.5 \cdot 5 = 2.86$ m^3 min per hp or $Q_i = 717$ m^3/min $= 11.95$ m^3/s.

The calculation using the formula (10) with $S_{exp.} = 16.8$ m^2, $V_m = 10$ km/h (2.8 m/s) and the calculated air flow $Q_i = 11.95$ m^3/s showed that the NO_x concentration in the air is lower than that with a stationary machine with ICE. However, the calculation by the above method showed that the concentration of NO_x increases with the increase in the amount of air and the power of the machine with ICE (Fig. 3). Thus, it is possible that when the power of a machine with an internal combustion engine is equal to 500 hp and an air flow rate is 23 m^3/s, the concentration of NO_x in the air exceeds $C_{mac.NO_2}$ equal to 5 mg/m^3.

This situation can be aggravated when the air flow is determined as for stationary equipment, and then the same air-flow is used to ventilate the output when the ICE machines moves. The considered case is illustrated by the graphs in Fig. 4. From the analysis of these graphs, it follows that at the speed of movement of machines in the area located below the curves corresponding to fixed values of N_1 and N_2, the concentration of NO_x in the air will exceed the standard value. Thus, reducing the speed of movement of machines with ICE will lead to an increase in the concentration of NO_x in the air. This is explained by the fact that a decrease in the speed of movement of machines with ICE with the same air flow results in a decrease in the speed of air relative to emitting pollutants from a machine with ICE [8]. In the extreme case, when the relative air velocity relative to cars with ICE corresponds to zero, the concentration of pollutants reaches a maximum value corresponding to their concentration in exhaust emissions [9, 10].

A similar scenario will take place in case of movement of two machines with ICE having different engine power.

With the speed of machines with ICE 10 km/h, the provision of $S_{mac.NO_2}$, equal to 5 mg/m^3, is possible only at the air flow rates indicated in Table 2.

Therefore, when ensuring standard concentrations of pollutants contained in the exhaust gases of cars with internal combustion engines in the air of a mine, it is necessary to take into account the geometrical parameters of the workings, the speed of movement of the machines and the number of them in working.

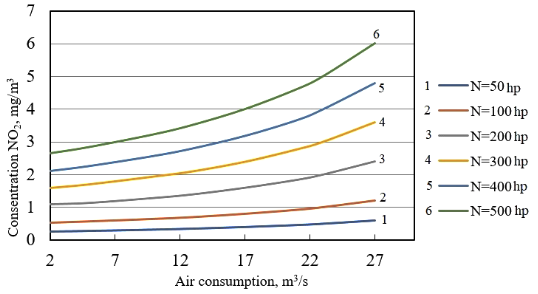

Fig. 3. Dependence of NO_x *concentration in the air on the power of the machines with ICE and the amount of air*

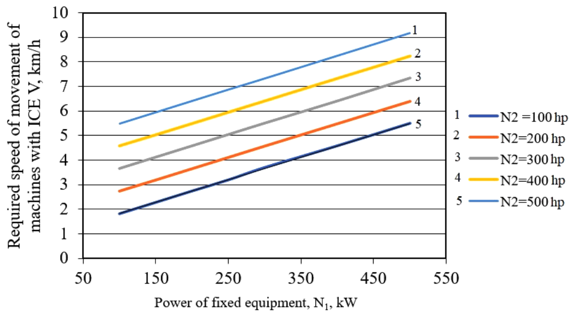

Fig. 4. Dependence of the required speed of movement of machines with ICE on the power ratio of fixed and moving self-propelled equipment

Calculation of specific air flow for actual conditions. For example, the calculation of specific air flow rates for mountain transport equipment with engines meeting the Tier III environmental standard was performed. The performed evaluations showed that this standard conforms to the EU standard for off-road vehicles Stage IIIA and occupies an intermediate place between the Euro 3 and Euro 4 standards used in the Russian Federation [11, 12].

The parameters of the mining transport equipment considered below, necessary for calculating specific air flow rates, including environmental standards for pollutant emissions, maximum allowable concentrations of pollutants and the established efficiency of gas cleaning in catalytic converters, are shown in Table 3.

In addition, we use the following parameters for calculations:

- air density: $\rho_{air} = 1.25$ kg/m^3;

- initial volume concentration of oxygen in the air entering into the engine of the machine: $C_0 = 20.8$ %;

Table 2

The required volume of air (m^3/s) for airing the mine with two moving machines with ICE with powers of N_1 and N_2

N_1, hp	$N_2 = 100$ hp	$N_2 = 200$ hp	$N_2 = 300$ hp	$N_2 = 400$ hp	$N_2 = 500$ hp
50	2.66	3	3.53	4.3	5.6
100	5.35	6.2	7.4	9.7	–
150	8.1	9.55	12.1	–	–
200	10.9	13.2	–	–	–
250	13.8	17.6	–	–	–
300	16.9	–	–	–	–
400	23.9	–	–	–	–

- the stoichiometric amount of oxygen required for complete combustion of the total amount of diesel fuel: $l_0 = 3.35$ kg/kg.

Results. Let us consider an example of calculating the specific consumption of air supplied to ventilate the workings of a mine using the exhaust gas dilution factor from self-propelled diesel equipment and providing standardized oxygen concentration, using the example of Sandvik LH307.

Specific air consumption for nitrogen oxides for Tier III will be: $q_{sp.NO_x} = j_{NO_x} / K_{ef} \cdot C_{mac.NO_x} = 50/3.5 \cdot 5 = 2.86\ m^3/\text{min}$ per hp.

Carbon monoxide specific air consumption for Tier III will be: $q_{sp.CO} = j_{CO}/K_{ef} \cdot C_{mac.CO} = 43.3/5.1 \cdot 20 = 0.42$ m^3/min per hp.

Specific air consumption for oxygen will be: $q_{O_2} = 0.015 \times \times q_{fl} \cdot l_O/(\rho_{air} \cdot (CO - 20)) = 0.015 \cdot 3.35 \cdot 33.5/(1.25 \cdot (20.8 - - 20)) = 1.68$ m^3/min per hp.

The calculation of specific air flow for the rest of the equipment was made according to this example.

The values of specific air flow rates for main equipment planned for loading and haul operations are presented in Table 4.

The analysis of the data presented in Table 4 suggests that for Tier III environmental standard, the maximum specific air flow rate is necessary to dilute emissions of nitrogen oxides. The flow rate is 2.86 m^3/min per hp. Specific air flow rates for diluting carbon monoxide emissions and ensuring the standard oxygen content have a lower value of 0.42 m^3/min per hp and 1.68–2.63 m^3/min per hp, respectively. The transition of engines of machines to the environmental standard Tier IV can lead to the situation when basis for calculation of air amount will be the specific air consumption for oxygen.

The authors analyzed the data related to efficiency of purification of exhaust gases using neutralizers on oxides of nitrogen and carbon monoxide. The results demonstrated that gas cleaning helps to reduce emissions of carbon monoxide and nitrogen oxides by 80 and 71 %, respectively.

In confirmation of the relevance of the study, Professor S. G. Gendler made an assessment of the concentration of nitrogen oxides in the air, taking into account the direction of movement of equipment and air, as well as their speeds.

The calculation of specific air consumption according to the method developed by the authors has demonstrated that its maximum value for the Tier III environmental standard is achieved when diluting emissions of nitrogen oxides and is equal to 2.86 m^3/min per hp.

The use of mining equipment in Russia that complies with Tier III standards allows us to conclude that it is possible to reduce the norm of specific amount of air required to dilute the gases generated by the operation of machines with ICE, compared with the earlier recommended value of 5 m^3/min per hp [13].

Conclusions. Studies performed in the area of calculating the specific air flow rate by exhaust dilution factor have shown the possibility of significantly reducing the amount of air supplied to the atmosphere of the mine to dilute harmful impurities to standard values.

Using the equipment that meets more modern environmental standards of fuel entails a reduction in the amount of air supplied to the working. Consequently, this will increase the service life of equipment involved in the ventilation of mine workings, and will significantly reduce the capital costs of mining enterprises, which will generally lead to a positive economic effect.

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Table 3

Input data for calculating specific air flow rates for diluting pollutant emissions and ensuring regulatory oxygen content

Machine name	Sandvik LH307	Sandvik TH320	RDH HM800-20	ST 1030
Emissions of nitrogen oxides according to the standard Tier III, j_{NO_x}, mg/min per hp	50	50	50	50
Efficiency of gas cleaning by nitrogen oxides, K_{efNO_x}	3.5	3.5	3.5	3.5
Carbon monoxide emissions according to Tier III, j_{CO}, mg/min per hp	43.3	43.3	43.3	43.3
The efficiency of gas cleaning for carbon monoxide, $K_{ef.CO}$	5.1	5.1	5.1	5.1
Nominal fuel consumption q_{fl}, kg/min per hp	33.5	52.5	45.2	46.1
Emissions of nitrogen oxides according to the standard Tier IV, j_{NO_x}, mg/min per hp	5	5	5	5
C_{mac} on nitrogen oxides in terms of NO_2, mg/m^3	5	5	5	5
C_{mac} on carbon monoxide mg/m^3	20	20	20	20

Table 4

Specific air consumption norms for exhaust gas dilution factor from self-propelled diesel equipment and ensuring regulatory oxygen concentration

Machine name	Sandvik LH307	Sandvik TH320	RDH HM800-20	ST 1030
Carbon monoxide specific air consumption for Tier III standard, m^3/min per hp	0.42	0.42	0.42	0.42
Specific air consumption for nitrogen oxides for Tier III standard, m^3/min per hp	2.86	2.86	2.86	2.86
Specific air consumption for oxygen, m^3/min per hp	1.68	2.63	2.26	2.3
Specific air consumption for nitrogen oxides for Tier IV standard, m^3/min per hp	1.0	1.0	1.0	1.0

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Розрахунок кількості повітря для провітрювання гірничих виробок під час роботи самохідного дизельного обладнання

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Мета. Розробка методики для визначення необхідної кількості повітря для провітрювання виробок за фактором вихлопних газів від двигунів внутрішнього згоряння (ДВЗ).

Методика. Для визначення фактичного значення ефективності очищення (нейтралізації) вихлопних газів від самохідних дизельних машин, викиди від двигунів яких відповідають екологічному стандарту Tier III, була здійснена обробка даних натурних вимірювань за величиною концентрації оксиду вуглецю (CO) і оксидів азоту (у перерахунку на NO_2) після каталітичного нейтралізатора, проведених в умовах „Об'єднаного Кіровського рудника" та Малеївського, Тишинського й Долинного рудників ТОВ „Казцинк" (РФ).

Результати. Розрахунок величини питомої витрати повітря за розробленою авторами методикою показав, що його максимальне значення для екологічного стандарту Tier III досягається при розбавленні викидів окислів азоту та дорівнює 2,86 $м^3$/хв на к.с.

Наукова новизна. У ході дослідження в області ефективності очищення вихлопних газів після нейтралізатора був виведений коефіцієнт газоочищення й застосований у методиці з розрахунку кількості повітря. Проведені дослідження в області розрахунку питомої витрати повітря по фактору розрідження вихлопних газів показали можливість значного зменшення кількості повітря, що подається до атмосфери виробки, для розведення шкідливих домішок до нормативних значень.

Практична значимість. Розрахунок кількості повітря за сучасними стандартами дизельного обладнання дозволить зменшити витрати на провітрювання гірничих виробок. Це збільшить ресурс роботи обладнання, задіяного на провітрювані гірничих виробок, значно зменшить капітальні витрати гірничорудних підприємств, що призведе до позитивного економічного ефекту.

Ключові слова: *вентиляція, вихлопні гази, каталітичний нейтралізатор, витрата повітря, самохідне дизельне обладнання, ефективність газоочищення*

Расчет количества воздуха для проветривания горных выработок при работе самоходного дизельного оборудования

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Цель. Разработка методики для определения необходимого количества воздуха на проветривание выработок по фактору выхлопных газов от двигателей внутреннего сгорания (ДВС).

Методика. Для определения фактического значения эффективности очистки (нейтрализации) выхлопных газов от самоходных дизельных машин, выбросы от двигателей которых соответствуют экологическому стандарту Tier III, была осуществлена обработка данных натурных измерений по величине концентрации оксида углерода (CO) и окислов азота (в пересчете на NO_2) после каталитического нейтрализатора, проведенных в условиях „Объединенного Кировского рудника" и рудников Малеевский, Тишинский и Долинный ООО „Казцинк" (РФ).

Результаты. Расчет величины удельного расхода воздуха по разработанной авторами методике показал, что его максимальное значение для экологического стандарта Tier III достигается при разбавлении выбросов окислов азота и равно 2,86 $м^3$/мин на л.с.

Научная новизна. В ходе исследования в области эффективности очистки выхлопных газов после нейтрализатора был выведен коэффициент газоочистки и применен в методике по расчету количества воздуха. Проведенные исследования в области расчета удельного расхода воздуха по фактору разжижения выхлопных газов показали возможность значительного уменьшения количества воздуха, подаваемого в атмосферу выработки, для разбавления вредных примесей до нормативных значений.

Практическая значимость. Расчет количества воздуха по современным стандартам дизельного оборудования позволит уменьшить затраты на проветривание горных выработок. Это увеличит ресурс работы оборудования, задействованного на проветривании горных выработок, значительно уменьшит капитальные затраты горнорудных предприятий, что приведет к положительному экономическому эффекту.

Ключевые слова: *вентиляция, выхлопные газы, каталитический нейтрализатор, расход воздуха, самоходное дизельное оборудование, эффективность газоочистки*

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