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ASSESSMENT OF PROTECTION LEVEL OF DUST RESPIRATORS AT COAL MINES

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ОЦІНКА СТУПЕНЮ ЗАХИСТУ ПРОТИПИЛОВИХ РЕСПІРАТОРІВ НА ВУГІЛЬНИХ ШАХТАХ

Purpose. To determine the boundary of coal dust concentration in the mine workings air in terms of using filter respirators at coal mines.

Methodology. Protective efficiency of filtering respirators is calculated on the basis of determination of geometric mean value of manufacturing protection coefficient of filter respirator offered by the American National Standards Institute (ANSI) and the National Institute for Occupational Safety and Health (NIOSH).

Findings. Dependence of undermask dust concentration on air dustiness within mine workings, respirator protection coefficient, and insulating properties of half-masks has been determined. As a result of modeling the distribution of probability of dust concentration values under the mask, it has been determined that the boundary of dust concentration providing safe use of РПА respirator is 10 MAC.

Originality. Protective coefficients of domestic filter respirators under working conditions have been substantiated taking into account aspiration value along obturation line caused by half-mask slipping while operating as well as changes in dust concentration coefficients in the working zone air.

Practical value. It has been determined that filter respirators of РПА type can be used safely in terms of up to 100 mg/m^3 dust concentration.

Keywords: *dust respirator, filter, coefficient of protection, dust load, coal mine*

Introduction. Underground mining is connected not only with hazard to life but also with the effect of harmful manufacturing factors such as dust, noise, vibration etc. Nowadays up to 70 % of miners work under harmful conditions. Depending on natural coal humidity, air dustiness with lacking antidust means is 50…750 mg/m^3. In certain cases, it reaches up to 2000…2500 mg/m^3 and more [1]. Having entered the respiratory organs, noninjurious dust can result in various occupational diseases including irreversible and incurable ones – such as pneumoconiosis. It causes damage not only to workers and to their families but also to the society; the damage can be of demographic, social or economic character. Since the fact that collective means of protection do not allow decreasing air dustiness down to safe concentrations, nowadays dust respirators are still the most accessible protection means for miners. While calculating values of allowable dust load for miners, it is extremely important to assess the efficiency of filter respirator protection.

Analysis of the recent research and objective of the paper. Dozens of manufacturing research studies have been carried out to assess the efficiency of respiratory protective device (RPD) in different countries. The studies included simultaneous measuring of harmful substance concentration both under half-mask and within the breathing zone. The obtained results have shown that when a half-mask matches the face completely being used correctly (timely), suctions of unfiltered air through the gaps between half-mask and face are the main reasons for deterioration of protective properties of respirators [2]. Various factors influence the formation and size of the gaps: defects in headband fixation system, regular movements of a man while operating, climatic parameters etc. That is why respirator efficiency (PC protection coefficient – relation of external pollution load to the undermask one) is a variable and unpredictable value which can vary within wide range of values from 120 to 20 and even down to 1 if a half-mask does not match anthropometric facial characteristics.

A new parameter called *assigned protection factor* (APF) has been introduced on the basis of the research carried out in the USA. It shows the rate of contamination decrease in the inhaled air being ensured by the respirator model in terms of its correct and timely use by instructed and trained workers when the masks are selected individually on the basis of certain sizes. Taking into account possible mask slipping and more suction of unfiltered air through the gaps, the APF for filter elastomeric half-masks of any protection class is equal to 10 in the USA and to 20 in Great Britain [3]. Such twofold distinction in half-masks is explained by different approaches to the efficiency assessment in two countries. USA experts considered the worst case – use of respirator during 8-hour shift. As for the UK, specialists arrived at an idea that it was impossible to wear a half-mask during the whole working day without any breaks; besides they decided that "time defense" would reduce negative effect on a worker.

As for the USSR, Ukraine, and Russian Federation respirator protective efficiency was previously assessed only on the basis of laboratory measurements that resulted in considerable overstatement of the assigned half-mask efficiency comparing to the real one (Fig. 1) [4]. For instance, DNAOP 0.00-1.04-07 "Rules to select and use respiratory protective devices" (State Regularly Legal Act on Work Safety) indicates that protective coefficient of either РПА or "Пульс" respirator is equal to 100; consequently it can be used in terms of dust concentration being up to 500 mg/m^3 (Appendix B.1). The Table also demonstrates that 3M half-mask of 6000 series with P2 filter has protection level being just 50; thus, it can be used only up to 200 mg/m^3. In this context it is considered that the product by "3M" company is of the highest quality among the manufacturers of protective equipment.

Unsolved aspects of the problem. Despite the fact that national legislation covers a number of regulatory legal acts to protect the workers against harmful manufacturing factors, use of knowingly unreliable half-masks in terms of high air dustiness results in occupational diseases of miners in the forms of pneumonoconiosis and bronchitis. The reason is in general character of the requirements represented in such documents that do not solve specific problems – how to select and manage use of respirators (as well as how to assess their efficiency in terms of their practical use).

For instance, DNAOP 0.00-1.04-07 "Rules to select and use respiratory protective devices" has no unambiguously determined assigned protection coefficients for filter respirators of various structures. Moreover, paragraph 6.2.2 (note) recommends using half-masks with dust resistant replaceable filters in terms of 400–500 mg/m^3 coal dust concentration. According to all the standards to select and use respiratory protective devices being effective in the USA, Great Britain and German (OSHA Standard: "29 CFR 1910.134 Respiratory protection"; BS 4275-1997. "Guide to implementing an effective respiratory protective device programme"; DIN EN 529:2005 "Atemschutzgeräte – Empfehlungen für Auswahl, Einsatz, Pflege und Instandhaltung – Leitfaden") if there is such dustiness, one must not use even the highest quality filter respirators.

DSTU EN 529:2006 Standards "Respiratory protective devices. Recommendations for selection, use and maintenance. Regulation (EN 529:2005, IDT)" states that the selection of filter respiratory protective devices should follow the rule that minimum required protection level should be higher than the determined national protection coefficient (paragraph 9.2.3) which is to be indicated in Appendix C of the regulatory document. However, the mentioned Appendix does not contain information concerning values of national protection coefficients. Lack of the data does not allow applying DSTU EN 529 to select filter respirators under specific working conditions.

Thus, unfortunately, strict observation of the requirements of the national legislation of Ukraine does not reduce disease risk of the workers as well as does not prevent use of knowingly inefficient respiratory protective devices.

Objective of the research. To determine safe range of coal dust concentration to provide high-efficiency protection of miners while using filter respirator devices both on the basis of the analysis of published data on air dustiness within coal mine workings and on the basis of the data concerning protection coefficient of filter respirators.

Presentation of the main research and methods. DSTU EN 529:2006 applies several parameters to characterize the efficiency of respiratory protective devices. One of the parameters is manufacturing protection coefficient

$$PF_p = \frac{C_0}{C_i}, \quad (1)$$

where C_0 is aerosol concentration within a test chamber, mg/m^3; C_i is aerosol concentration within undermask respiratory space, mg/m^3.

However, PF_p does not take into consideration a number of factors described before and being able to deteriorate considerably protective efficiency of respiratory protection devices. Consequently, the concept of assigned protection factors (APF_p) has been introduced into the standard. The concept shows which real protection level can be reached in terms of using respirators at the workplace by 95 % of instructed and trained workers. To calculate the parameter, W. R. Myers proposed to use geometric mean value of manufacturing protection coefficient ($GMPK_p$)

$$APF_p = \frac{GMPF_p}{GSD^{zp}}, \quad (2)$$

where $GMPF_p$ is geometric mean value of manufacturing protection coefficient; GSD is standard geometric deviation, $GMPF_p$; zp is coefficient dependant on the assigned confidence interval (having performed statistical analysis of measurements of *RPD* protection properties within workplaces, scientists D. I. Campbell and S. W. Lenhart proposed to limit the use of respirator facepieces of the known type so that in 95 % cases of their use there would be the required protection efficiency at the workplace).

A large amount of harmful substances entering the worker's organism per shift affects considerably his/her health. In this case it is vital to determine PK_p minimum value of respirator per shift as its value is the determinative one while calculating such an important parameter as dust load. Let us assume that, for instance, air contamination is approximately 50 mg/m^3, inhaled air consumption is 0.03 m^3/min, total time of being within a dust-loaded space is 360 min, then dust amount entering the lungs within respirator use will have the following value, mg

$$P = C_0 Q_0 t = 50 \cdot 0.03 \cdot 360 = 540,$$

where C_0 is dust concentration within working zone air, mg/m^3; Q_0 is general air flow through respirator, m^3/min; t is time, min.

Let us assume that under such conditions a worker is using a filter respirator for five hours, its protection level (PF_p) is equal to 100 units within four hours while within one hour its protection level is equal to 10 due to mask slipping during the work, filter changing, necessity to talk and other reasons when mask is not adjacent properly to the face. Then dust load is equal to, mg

$$P = \frac{1}{PF_p} C_0 Q_0 t = \frac{1}{100}\left(50 \cdot 0.03 \cdot 240\right) + \\ + \frac{1}{10}\left(50 \cdot 0.03 \cdot 60\right) = 3.6 + 9 = 12.6.$$

While analyzing the obtained results we can see that to reduce negative effect of dust aerosol on a worker, it is PF_p minimum value that is important to be evaluated.

Experts of the American National Standards Institute (ANSI) and the National Institute for Occupational Safety and Health (NIOSH) have solved the problem of determining $GMPF_p$ values to calculate APF_p in favor of the specifying the least PK_p values being determined as lower PF_p confidence interval for 5 % of observations of total number of measured values.

Taking into account a large number of measurements to determine respirator ficiency, European Union countries began using their statistical analysis. For example, T. J. Nelson has introduced undermask concentration of harmful substance as the function of distribution of air contamination concentration, coefficient of respirator protection and penetration through the gaps along obturation line.

$$C_i = C_0\left(\frac{1}{PF_p} + K_{pg}\right), \quad (3)$$

where K_{pg} is the coefficient of penetration through the gaps along the obturation line.

Sequence of calculation is the setting of the parameters of distributions of the external dust concentration and manufacturing coefficient of respirator protection. In this context the coefficient of penetration through the gaps along the obturation line can be determined by calculations based on the formula proposed by W. C. Hinds

$$K_{pg} = 1 - 5.5k^{2/3} + 3.77k \quad \text{if } k<0.009$$

and

$$K_{pg} = 0.819\exp(-11.5k) + 0.0975\exp(-70.1k) \\ \text{if } k > 0.009,$$

where $k = \frac{DL}{Q_a}$; L is the tube length equivalent to gap, m; D is the diffusion coefficient; Q_a is air consumption through the gaps, dm^3/min.

Air suction through the gaps along the obturation line can be calculated using the formula proposed by D. Campbell

$$Q_a = K(\Delta P)^a d_0^b,$$

where K, a and b are constants, ($K = 0.05$–0.1, $a = 0.56$–0.92, and $b = 0.5$–1); ΔP is pressure differential within the respirator filter, Pa; d_o is the hole diameter equivalent to a gap, mm.

Dust generation depends on specific features of mining conditions and the applied techniques (coal hardness, abundance of water in mines, methods of extraction, transportation etc.). Dust content within the zones where shaftmen, coal shearer operators, operators of supports for longwall set of equipment work can reach tens and thousands of milligrams per1 m^3 [4]. According to the studies by E. N. Medvedev average dustiness in mine workings is within the range of 150–350 mg/m^3 (Table 1).

Table 2 represents the results of PF_p determination in terms of national respirators of РПА type within coal mines. Data are taken from the published studies in papers [5, 6].

Coefficients of suction along the obturation line of half-mask of ПР-7 type were determined taking into account difference of pressure differentials between a half-mask being air-tightly fixed and put on a man ranging from 1.5 up to 14 units, in this context average $K_{al} = 6.6 \pm 3.5$ [7]. The modeling was performed for widely used РПА mining half-mask, parameters of protection coefficient which we obtained (average and standard deviation – values in Table 2 and values of suction coefficient within miners' workplaces) and data on dust concentration (Table 1). Cristal Ball program was used to perform calculations; in this program, distribution type for each specific case was set. Let us take a single set of values for C_0, PF_p and K_{pd} in terms of 30 dm^3/min air consumption. Most probable values – modes (peak values of dust concentration) of each parameter with specific frequency of occurrence are introduced into equation (3), and value of C_i undermask concentration is

Table 1

Values of average dust concentrations in the air of mine workings within the mines of the association

Parameters	Krasnoarmiiskvuhillia Myrnohradvuhillia	Dobropillia-vuhillia	Pavlohrad-vuhillia	Selidov-vuhillia	Ukrzakhid-vuhillia
Average dust concentration, mg/m^3	317	305	286	212	164
Standard geometric deviation	5	3	4	4	2

Table 2

Results of manufacturing research of filter respirators

Author of the research	Place of research	Number of measurements, pcs.	Type of RPD	Average PF_p RPD
Golinko [5]	Coal mines	30	РПА	16±2.7
Kuzmichiov A. S. [6]		–	Ф-62Ш, РПА	99.9

calculated. The process was repeated for a large number of independent variables (Fig. 1).

Results. Fig. 2 represents averaged results of the dependence of undermask dust concentration upon air dustiness within the working zone for РПА respirator. On the assumption of the obtained data, probability of the fact that dust concentration under respirator mask will not exceed MAC (Figs. 3 and 4) in terms of continuous respirator use has been calculated.

Modeling results show that if a respirator is used in terms of 200 mg/m^3 dustiness, then probability of the fact that dust concentration under respirator mask will

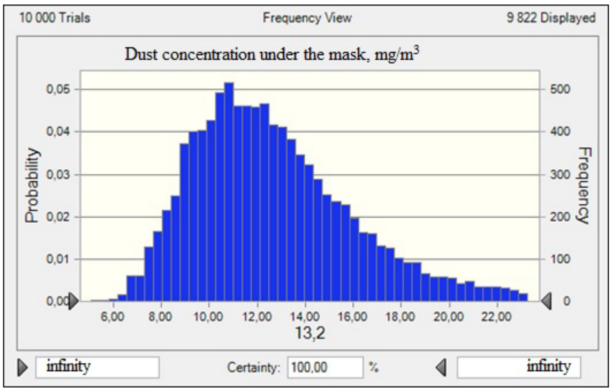

Fig. 1. Bar graph of distribution of dust concentration value probability under the mask of РПА respirator being built for GM C_0 = 317 mg/m^3; GSD C_0 = 4; GM $K_p^f = 0.5$ %; GSD $K_p^f = 0.1$; $K_l^a = 0.005$, for 30 dm^3/min air consumption

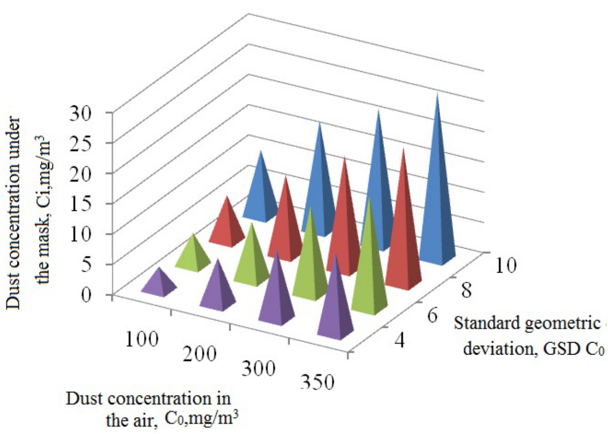

Fig. 2. Diagram of average dust concentration distribution within undermask space of РПА respirator

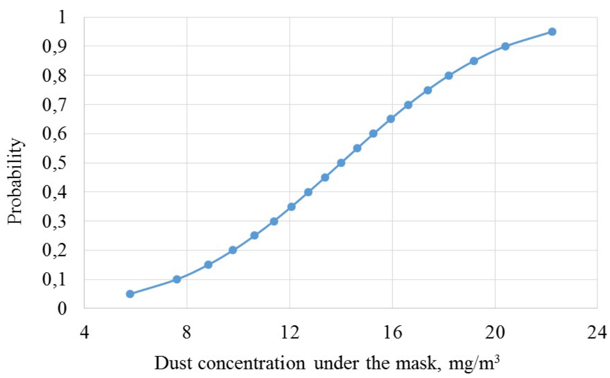

Fig. 3. Probability of dust concentration change within undermask space with continuous use of РПА respirator given 200 mg/m^3 dust concentration within a working zone

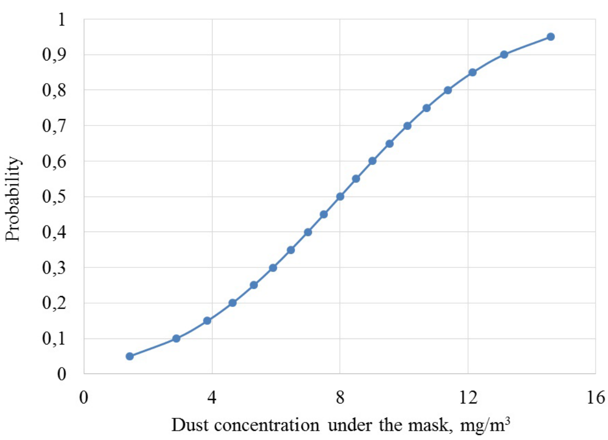

Fig. 4. Probability of dust concentration change within undermask space with continuous use of РПА respirator given 95 mg/m^3 dust concentration within a working zone

not exceed MAC (10 mg/m^3) is no more than 20 %; while for the dust with MAC 4 mg/m^3 such probability is equal to zero. At the same time, if air dustiness is less than 100 mg/m^3, such probability increases up to 80 %. Changeability in suction values the along half-mask obturation line as well as dust concentration within the air of working zone are the factors affecting protection properties of filter respirators most of all. Such suctions occurring during the work result in the increase in standard geometric deviation (Fig. 2). The worst results are recorded in terms of increase in standard geometric deviation up to 10. It can be explained by the decrease in penetration of coarse dust fraction under the mask due to the peculiarities of air aspiration that is showed in K_{pd} calculations proposed by Higgs.

Taking into consideration that continuous wearing of respirator during 6 hours is practically impossible, it can be concluded that use of respirators cannot prevent miners from having incurable and irreversible occupational diseases – pneumonoconioses (silicosis, anthracosis etc.); it can only reduce the risk of having such diseases. Consequently, they should be used in addition to efficient means of collective protection.

It is important to note that in the 1970-s in coal mines of Great Britain average dust concentration in terms of general mass was ~89 mg/m^3 [8]; whereas in the USA, since February 2016, maximum allowable concentration (MAC) of respirable dust fraction within the most dust-loaded workplaces of coal mines is going to be controlled in real time by means of personal PRM dust counter [9] (in terms of MAC of 1.5 mg/m^3 respirable dust fraction, concentration of all dust fractions is approximately equal to 7.5–30 mg/m^3). Consequently, our country has great unapplied reserves to improve operating conditions to be used for decreasing the rate of occupational diseases.

Conclusions. Dependence of undermask dust concentration on air dustiness in mine workings, protection coefficient of a respirator, and insulating properties of half-masks has been determined. As a result of modeling of the distribution of dust concentration values probability under the mask of РПА respirator it has been shown that the boundary of dust concentration for its safe use is 10 MAC, i.e. up to 100 mg/m^3.

In spite of the established opinion, using a half-mask cannot protect miners even in terms of its continuous wearing being impossible in practice. To reduce the rate of occupational diseases it is necessary to concentrate efforts on:

- reduction of air dustiness within breathing zone (advanced technology, automation, remote control, ventilation);
- development of devices and methods that allow having better control of air dustiness within breathing zone;
- improvement of quality and quantity of medical examinations for miners to detect occupational diseases at the initial stage as well as the increase in quality of preventive medical measures (phototherapy rooms etc.);
- decrease in standards for safe use of filter respirators in coal mines from 500 mg/m^3 down to 100 mg/m^3.

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Мета. Визначити межу концентрації пилу в повітрі гірничих виробок для використання фільтруючих респіраторів на вугільних шахтах.

Методика. Розрахунок ефективності захисту фільтруючих респіраторів ґрунтується на визначенні середньогеометричного значення виробничого коефіцієнта захисту фільтруючого респіратора, що запропонований фахівцями Американської асоціації промислових гігієністів (ANSI) і Національного інституту охорони праці США (NIOSH).

Результати. Встановлена залежність підмаскової концентрації пилу від запиленості повітря в гірничих виробках, коефіцієнта захисту респіратора та ізолювальних властивостей півмасок. У результаті моделювання розподілу ймовірності значень концентрації пилу під маскою встановлено, що межа концентрації пилу для безпечного використання респіратора РПА становить до 10 ГДК.

Наукова новизна. Полягає в науковому обґрунтуванні коефіцієнтів захисту вітчизняних фільтруваньних респіраторів у промислових умовах з урахуванням величини підсмоктування за смугою обтюрації й зміни концентрації пилу в повітря робочої зони.

Практична значимість. Доведено, що фільтруючі респіратори типу РПА можна безпечно використовувати при концентрації пилу до 100 мг/м^3.

Ключові слова: *протипиловий респіратор, фільтр, коефіцієнт захисту, пилове навантаження, вугільна шахта*

Цель. Определить границу концентрации угольной пыли для использования фильтрующих респираторов на угольных шахтах.

Методика. Расчет эффективности защиты фильтрующих респираторов основывается на определении среднегеометрического значения производственного коэффициента защиты фильтрующего респиратора, предложенного специалистами Американской ассоциации промышленных гигиенистов (ANSI) и Национального института охраны труда США (NIOSH).

Результаты. Установлена зависимость подмасочной концентрации пыли от запылённости воздуха в горных выработках, коэффициента защиты респиратора и изолирующих свойств полумасок. В результате моделирования распределения вероятности значений концентрации пыли под маской респиратора РПА установлено, что граница его безопасного использования составляет до 10 ПДК.

Научная новизна. Заключается в научном обосновании коэффициентов защиты отечественных фильтрующих респираторов в производственных условиях с учетом величины подсосов по полосе обтюрации и изменения концентрации пыли в воздухе рабочей зоны.

Практическая значимость. Установлено, что фильтрующие респираторы типа РПА можно безопасно использовать при концентрации пыли до 100 мг/м^3.

Ключевые слова: *противопылевой респиратор, фильтр, коэффициент защиты, пылевая нагрузка, угольная шахта*

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DETERMINATION OF AREAS OF ATMOSPHERIC AIR POLLUTION BY SULFUR OXIDE EMISSIONS FROM MINING AND METALLURGICAL AND ENERGY GENERATING ENTERPRISES

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ВИЗНАЧЕННЯ ЗОН ЗАБРУДНЕННЯ ГІРНИЧО-МЕТАЛУРГІЙНИМИ ТА ЕНЕРГОГЕНЕРУЮЧИМИ ПІДПРИЄМСТВАМИ АТМОСФЕРНОГО ПОВІТРЯ ОКСИДАМИ СІРКИ

Purpose. Development of methods and software for determining levels and zones of atmospheric air pollution by emissions from mining and power generating companies that contain significant volumes of sulfur oxides.

Methodology. The forecast of the level of atmospheric air pollution by sulfur-containing emissions from mining and power generating companies is based on a mathematical model for calculating the concentration of sulfur dioxide, which takes into account the processes of its oxidation, as well as the formation and evaporation of sulfuric acid in the atmosphere. The numerical method is based on the joint solution of the equations of convective-diffusion