Research of Operational Properties of Household Fabrics for Production of Protective Masks

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Abstract. Experimental studies have been conducted to determine the operational properties of fabrics used for the manufacture of protective masks. For the experimental study, 22 different fabrics were used, which are available in everyday life. Determination of the operational properties was carried out according to three indicators: the penetration coefficient of the test aerosol, paraffin oil (filtering property), breathing resistance (ergonomic property), resistance to dusting (protective action period) in accordance with the requirements of DSTU EN 149-2017 standard.

According to the results of the experimental study to determine the operational properties of fabrics: breathing resistance, penetration coefficient and resistance to dust, it was found that out of the twenty-two samples tested, only eight can be used for the manufacture of protective masks, since their characteristics are able to provide a sufficient level of protection from minimal physiological impact on human (wool, two-thread cloth, velor, tricotin, jersey, frieze and satin). Theoretical calculation of the operational properties of protective masks, which can be made of these fabrics, based on experimental data allowed to make their compliance with the first class of protection according to the requirements of DSTU EN 149-2017.

The scientific novelty is to clarify the relationship between the operational properties of fabrics and the operational properties of protective masks.

Introduction

The emergence of the coronavirus "SARS-CoV-2" (the official name is "COVID-19"), which according to the existing statement is transmitted by airborne transmission, caused an acute shortage of filter respirators.

Due to the significant increase in the required volume of personal respiratory protective devices (PRE), their manufacturers have not been able to meet all the needs of consumers in time. This forced citizens to start making protective masks from various improvised materials. They received considerable help through various Internet resources with the detailed description of the algorithm for making protective masks on their own. In most cases, ordinary fabrics that are present in everyday life were used to create them. Of course, when choosing the fabric for the manufacture of the protective mask, an urgent question arises regarding ensuring protective efficacy against the dangerous virus.

Problem formulation

In the presented literature sources [1-5] studies on the mechanisms of capture of aerosol systems by fibrous materials are given. In most cases, the evaluation of the protective effectiveness is based on solid or liquid particles with a size of 5 to 10 μm. However, when a person coughs, sneezes or speaks, the most dangerous drops are usually up to 1 to 2 μm in size. Therefore, it becomes necessary to conduct experimental studies to establish the protective properties of certain tissues in order to clarify the correction factors used for theoretical calculations of the protective effect of protective masks.

Analysis of publications

In its recommendations, the "World Health Organization" provided for the possibility of making protective masks from various fabrics. There are even requirements for them proposed by French Association for Standardization - to use only fabrics with the minimum filtration of solid particles of not less than 70% with the pressure drop of not more than 0.6 mbar / cm ^{2} [6]. These requirements are met by fabrics from cotton, polyester, cellulose, silk. However, unfortunately, this document does not contain more detailed explanations regarding the operational properties of these materials, which would allow to estimate the period of protective action.

Another study [7]) tested the effectiveness of the protective properties of eleven different fabrics: silk, linen, cotton and others in comparison with the medical mask. It is shown that the best results were obtained when using dense cotton and material for the manufacture of filters for dust collectors. However, again the properties of the materials are not disclosed, which does not guarantee a similar result when using similar fabrics. In another study [8], several household fabrics were tested for the effectiveness of retaining aerosol particles ranging in size from 30 to 100 nm. Their protective properties were compared with filter half masks of protection class 2. The authors focused more on the established particle sizes, which are the worst retained by fabrics. Unfortunately, the result obtained is difficult to use to select the necessary fabrics for the manufacture of the protective masks. It is more concerned with the development of the theory of filtration and established the patterns of capture by knitted fabrics. An interesting study was performed by the authors of paper [9], who evaluated the filtration efficiency of cotton, silk, chiffon, flannel as a function of aerosol particle size in the range from 10 nm to 10 μm. In addition, they considered the possibility of combining such tissues, but at the same time breathing resistance significantly increased, moreover, the authors noted that the main way of getting the virus into the undermask space of protective masks is their loose fit to the face.

Scientists from the University of Chicago and the Argonne National Laboratory were also asked to study the effectiveness of the protective properties of various fabrics (chiffon, cotton, flannel, silk, satin, polyester) [10]. The polydisperse test aerosol with the particle diameter from 0.001 to 6 μm was used for the study, covering both the size of the viruses and the range of aerosol particles for testing filter respirators. As a result, recommendations were given for fabrics (cotton in combination with the layer of chiffon made of polyester and spandex), from which you can make really effective protective masks. However, the researchers did not consider the time of protective action, i.e. how long they can be used.

Aim of Paper

Conducting experimental tests to determine the operational properties of fabrics that can be used to make protective masks and to establish the basic parameters of fabrics to calculate the term of protective action.

Materials and Methods

The operational properties of fabrics that affect the protective and ergonomic performance of protective masks include: coefficient of penetration of the test aerosol paraffin oil (filtering property); respiratory resistance (ergonomic property), resistance to dust (period of protective action) in accordance with the requirements of the standard [11]. Twenty-two commercially available fabrics were used for the experimental study. Their name and technical characteristics are given in the Table. 1. Before the study, the piece of 100 × 100 mm was cut from each fabric sample and weighed on VLO 200 laboratory scales to determine the surface packing density of the test sample.

The typical laboratory setup was used to determine the fabric penetration rate by the test aerosol. The schematic diagram shown in fig. 1, consisting of the aerosol generator, mixing and testing chambers and aerosol counter. The study procedure was performed according to the following algorithm. In the special test aerosol generator with the appropriate temperature (100 ^{0} C) of the test mixture of paraffin oil and air pressure provides a given range of aerosol particle sizes from 0.1 to 6 μm, which corresponds to the size of the viral variants. To ensure the required concentration of aerosol in the test chamber, where the test fabric sample is located, the test aerosol is first fed into the special mixing chamber. In it, due to the addition of clean air under the given pressure and the corresponding air flow rate, the required concentration in the range of 8-10 mg / m ^{3} is formed, which is fed into the test chamber with the flow rate of 3 dm^3 / min Determination of the penetration coefficient is performed using the special spectrophotometer. For this, the test aerosol sample is taken with the fabric sample and the sampling after the sample, allows you to determine how much the concentration has decreased through the fabric sample installed in the chamber. The penetration rate is calculated by the formula [12]:

$$K_n = C / C_0 \quad , \qquad (1)$$

where K_n is the penetration coefficient of the test aerosol; C is the concentration of the test aerosol to the test chamber, mg / m ^{3}; C_0 - concentration of the test aerosol after the material, mg / m ^{3}.

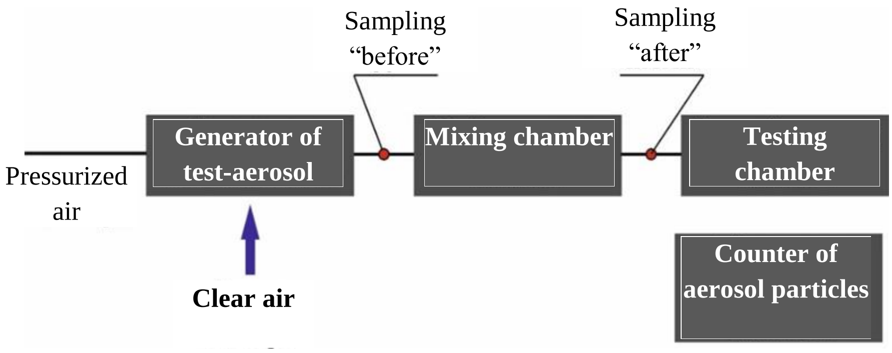


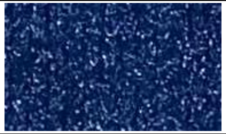
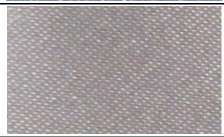
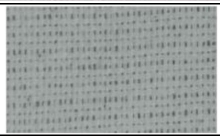
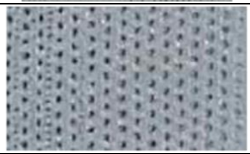
Fig. 1. Scheme and general view of the installation for checking the filtering properties of fabrics by test aerosol paraffin oil

Respiration resistance of the fabric was determined by the difference in pressure drop that occurs when blowing through them a certain amount of air flow. In this case, the air flow, as in the previous experiment was equal to 3 dm^3 / min Schematic diagram of the installation for determining the resistance of filter respirators is shown in fig. 2. Before carrying out studies it is necessary to define internal resistance R_1 of the clip at the set volume of the air consumption. Then the resistance of the sample is measured, which is experimentally investigated, at the given air flow rate R_2 [13]:

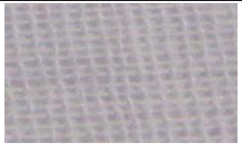
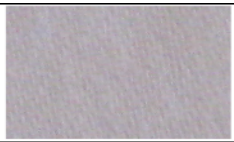
$$R = 9{,}81 \cdot (R_2 - R_1) \cdot K_1 \text{ , Pa} \qquad (2)$$

where R_2 is the measured value of resistance, mm WG; R_1 is the resistance to air flow of the clamp, mm WG; K_1 is the correction factor for temperature and pressure when determining resistance.

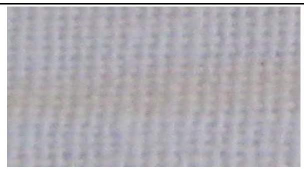
Table 1. Specifications of fabrics

Sample No.	Material name	Image of the material	Surface density of packing, g / m ^{2}	Linear density of threads, tex	Breaking load, N	Thickness, mm	Fiber diameter, µm
1	2	3	4	5	6	7	8
1.	Wool		2002	31	58	5	5
2.	Velor		260	58	98	6	3
3.	Atlas		180	7	85	5	5
4.	Silk		80	18	120	4	8
5.	Frieze		360	25	130	4	6
6.	Chiffon		40	15	85	6	5
7.	Two-thread cloth		240	25	115	5	6
8.	Tricotine		225	30	120	5	7

Continuation of Table 1.

1	2	3	4	5	6	7	8
9.	Jersey		270	25	135	6	12
10.	Biflex		135	15	150	7	11
11.	Gabardine		85	14	120	6	15
12.	Batiste		70	6	135	6	25
13.	Embroidery		110	9	110	4	20
14.	Calico		110	18	145	4	24
15.	Sateen		100	15	270	5	18
16.	Staple		65	35	130	4	14

End of Table 1.

1	2	3	4	5	6	7	8
17.	Knitted fabric viscose		180	14	85	3	8
18.	Linen		137	30	95	5	9
19.	Coarse calico		150	25	85	4	17
20.	Gauze		36	42	30	4	13
21.	Ticken		28	32	50	4	24
22.	Cotton		150	35	65	5	12

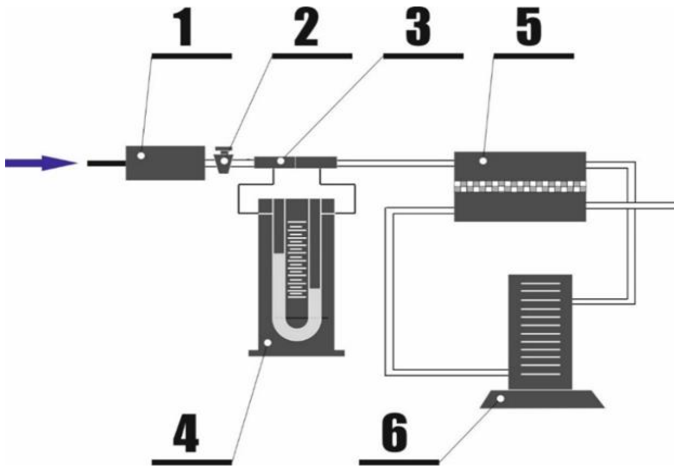


Fig. 2. Scheme and general view of the installation to check the pressure drop: 1 - pressure stabilizer; 2 - the valve; 3 - diaphragm; 4 - gauge; 5 - clamp for the material; 6 - compensation micromanometer "MKS"

The resistance of the material to dust was determined in the special dust chamber (fig. 3), where the piece of material was placed in the special prolong. The stand works as follows. Under pressure, the air from the compressor enters the stabilizer through the pre-cleaning filter. The amount of air is regulated by the valve and controlled by the manometer, based on the pressure drop across the calibrated diaphragm. For the formation of dust with the given dispersed composition (table. 2) in the vibrating dust generator is fed from 2 to 10 dm^3 / min clean air. The vibrating dust generator is the steel cup with inlet and outlet fittings, into which pre-crushed pieces of coal with the total weight of about 100 g are loaded. As a result of vibration of the chamber, there is the intensive self-grinding of these pieces to the dust state.

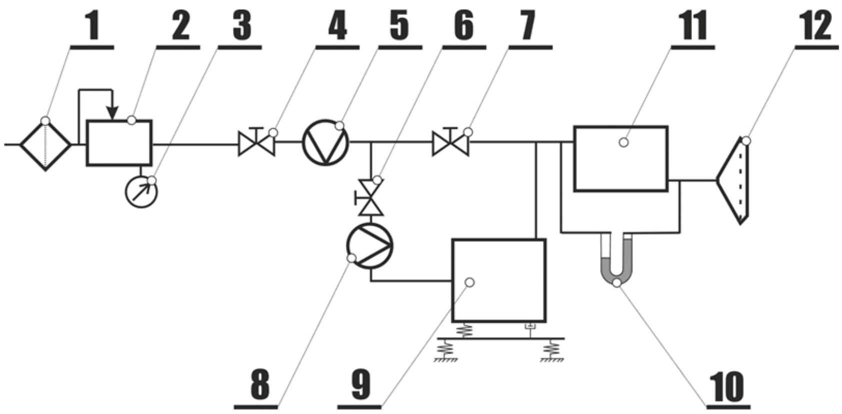


Fig. 3. Scheme and general view of the installation for testing respirators for dust resistance: 1 - pre-cleaning filter; 2 - gauge; 3 - pressure stabilizer; 4,6,7 - control valves; 5 - diaphragm; 8 - rotameter; 9 - dust loader; 10 - micromanometer; 11 - test chamber; 12 - cartridge

Table 2. Dispersed dust composition in test chamber [10]

Operating mode	Air flow through the generator dm ^{3} / min.	Mass fraction of particles,%				The average median size, μm
		<5 μm	-10 μm	10-30 μm	hore than 30 μm	
No.1	3	9	12	49	30	21
No.2	5	8	11	48	33	22

To speed up grinding, steel balls with the diameter of 10-15 mm are loaded into the generator chamber. Then the dust mixture is fed into the test chamber with the filter installed in the special adapter, which is connected to the air line with the aspirator, which provides air extraction with the flow rate of 3 dm^3 / min. The pressure drop across the filter during the accumulation of dust is monitored by the micromanometer at regular intervals.

The concentration of dust in the chamber was 400 mg / m ^{3}. The experiment was completed when the final pressure drop on the filters was 500 Pa. To determine the dust concentration, we used sampling for filters "AFA VP-10", with a diameter of about 36 mm at the rate of 2 dm^3 / min; laboratory scales "VLO 200" and the electronic stopwatch of "HS43" type. The pressure drop across the filter boxes was monitored using the compensating micromanometer "MKV 250" and adjusted for normal conditions. The studies were performed on dolomite dust with the average size of 1-5 μm, which allows to simulate aerosol particles released during sneezing or human conversation, on which viral particles can be transferred.

Research Results

The results of the research are shown in fig. 4-6.

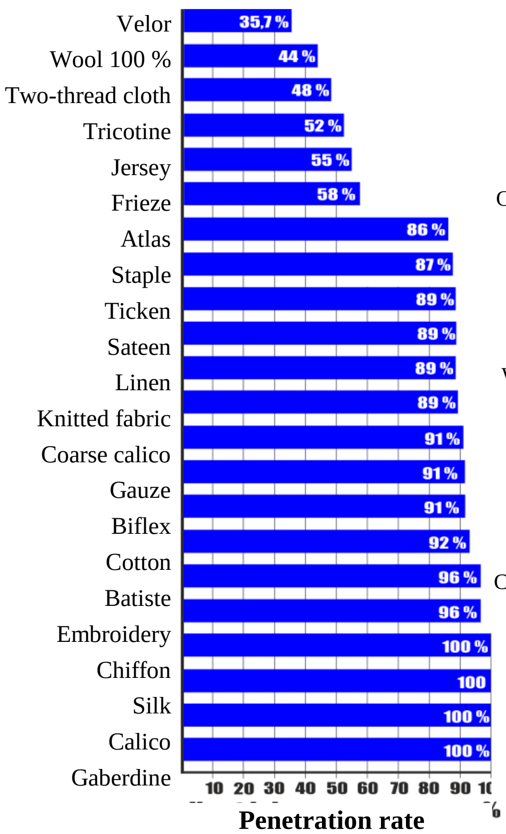


Fig. 4. The value of the penetration coefficient of the test aerosol on fabrics

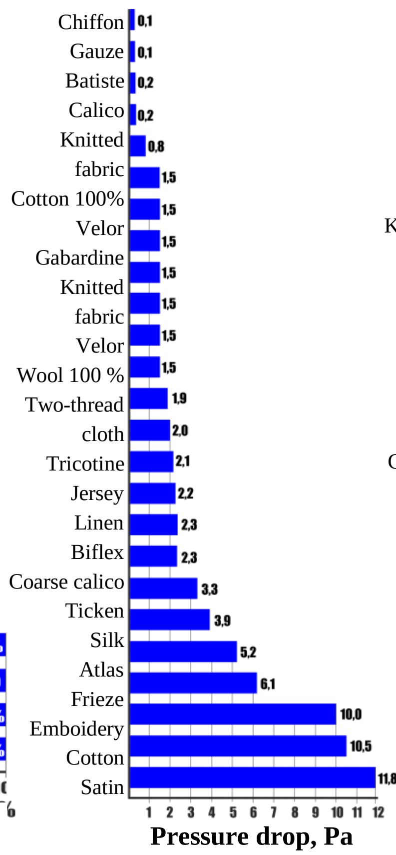


Fig. 5. The value of the fabrics pressure drop

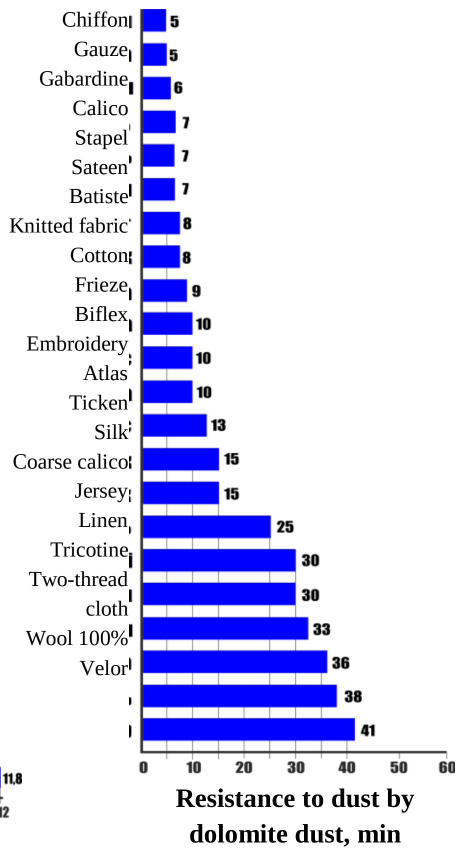
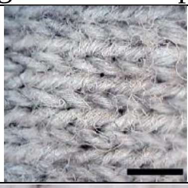
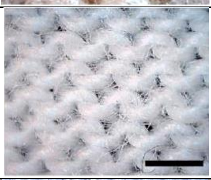
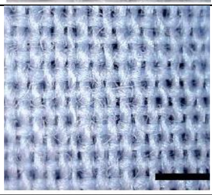
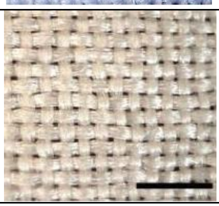


Fig. 6. Resistance to dust of fabrics

Experimental studies have shown that only seven fabrics (velor, wool, two-thread cloth, tricotine, jersey, frieze and sateen) will meet the requirements for filter materials from which respirators and filters are made. This is low respiratory resistance (<2 PA), minimal penetration rate (<60%) and high resistance to dust (> 30 minutes). Exceeding these values will lead to the fact that in the manufactured protective mask the person will feel some discomfort - or it will be very difficult to breathe or it will be characterized by low protective properties. Only a small number of fabrics meet the established requirements, which is explained primarily by the structure of the location of the fibers, the corresponding surface density and diameter of the fibers with the sufficient thickness of the fabric. Table. 3 shows the final results of experimental studies and the appearance of the structure of the tested fabrics under the microscope with the magnification of 300 times.

Table 3. Filtering and ergonomic characteristics of fabrics

Fabric	View of fabric structure (300 times magnification digital microscope)	Penetration coefficient	Pressure drop Pa	Resistance to dust, min
Wool (100%)		44	**1.5**	35
Two-thread cloth		48	1.9	36
Velor		35.7	1.5	41
Tricotine		52	2.7	33
Jersey		55	2.1	38
Frieze		58	6.1	10

Please note that the established indicators of the penetration coefficient of the test aerosol in protective masks will be slightly less than those obtained in laboratory conditions, through the large area of the working area compared to the area of the patches of the tested samples. This is due to the reduction of the air flow rate, which leads to the improvement in the process of trapping aerosol particles due to the diffusion effect [14].

To confirm the results obtained, given in table. 3 let's turn to the theory of filtration, which allows calculating the protective and ergonomic indicators of protective masks from the fabrics considered. First of all, let's determine the pressure drop that will be on the protective masks with the working surface area of 250 cm ^{2}. Given that at rest person makes 10-12 respiratory cycles with the volume of 2.5-3 dm ^{3}, the total amount of air that will pass through the mask will be about 30 dm ^{3} / min. Then the velocity of the air flow, which we take to calculate the pressure drop will be equal to 0.002 m ^{3} / s. The magnitude of the pressure drop is determined taking into account the viscous regime of the air flow (when the Reynolds number is less than one; R_e <1), according to the formula [15]:

$$\Delta p = \frac{4 \cdot v_0 \cdot \mu \cdot \beta \cdot H}{\alpha^2 \cdot \left(-\lambda - 0,5 \cdot \ln \beta\right)}, \text{ Pa} \tag{3}$$

where v_0 is air flow rate, m / s; a is the radius of the fiber, m; H is the thickness of the fabric, m; μ is dynamic viscosity of air, N × s / m ^{2}; λ is the correction factor; β is the packing density of the fibers, g/m ^{2}.

Table 4. Estimated values of the pressure drop of protective masks with the area of 250 cm ^{2}

Fabric name	Diameter of fibers, μm	Surface density, g / m ^{2}	Fiber packing density	Fabric thickness, mm	Correction factor, λ	Estimated pressure drop on the protective mask, Pa
Velor	8.4	260	0.092	4	0.4	9.1
Wool	5.6	200	0.071	5	0.5	13.8
Two-thread cloth	7.3	240	0.085	4	0.5	10.1
Tricotine	8.2	225	0.08	4	0.5	8.9
Jersey	9.6	270	0.096	5	0.6	11.5
Frieze	16.8	360	0.071	6	1.14	8.5
Atlas	2.4	180	0.045	4	0.5	22.5

The next indicator to determine the term of protective action is the penetration factor, which can be determined from the formula [16]:

$$K = e^{-\alpha}. \tag{4}$$

where α is the filtration coefficient, which is determined by the following formula [17]:

$$\alpha = \frac{2\beta \cdot H \cdot \eta_D}{\pi \cdot (1-\beta) \cdot a^2}. \tag{5}$$

where η_D is the coefficient of capture, which is due to diffusion deposition, we determine from the formula [18]:

$$\eta_D = 2,7P_e^{-2/3} \cdot (1 + 0,39k^{-1/3} \cdot P_e^{1/3} \cdot K_n) + 0,624P_e^{-1}, \tag{6}$$

where P_e is Peclet number, determined by the following formula [18]:

$$Pe = v_0 \cdot d_r / D_r, \tag{7}$$

where d_r is the particle diameter, μm; D_r is diffusion coefficient of the aerosol particle; k is the hydrodynamic coefficient, which takes into account the nature of the gas flow, is determined by the following formula [16]:

$$k = (-\lambda - 0{,}5\ln\beta)^{-1}, \tag{8}$$

where K_n is the Cudence number, determined by the following formula [19]:

$$K_n = \chi / a, \tag{9}$$

where χ is the free path length of the molecules of the medium, μm.

Based on the size of the aerosol particles of 0.3 μm, and the specified air flow rate of 0.002 m^3/s were determined by the values of the penetration coefficient through the protective masks, which have the surface area of 250 cm^2. The results of the calculations are given in the table. 5.

Table 5. The value of the penetration coefficient of protective masks with the area of 250 cm^2.

Fabric name	Diffusion coefficient, D_r, cm^2/s	Coefficient of capture, η_D	Filtration coefficient, α	Penetration coefficient, K
Velor	0.64	0.062	0.84	13.9
Wool		0.066	0.87	14.5
Two-thread cloth		0.035	0.73	9.7
Tricotine		0.054	0.80	12.8
Jersey		0.069	0.82	15.8
Frieze		0.071	0.91	19.3
Atlas		0.048	0.78	11.8

The period of protective action of fabric masks is determined based on the change in the coefficient of penetration of the filter during the accumulation of the certain dust sediment [20]:

$$t = \frac{10\log\left(\frac{K}{K_0}\right)}{\log\left(e^{-\alpha}\right)}, \tag{10}$$

where K_0 - initial penetration factor; K is the rate of penetration in the final term.

The calculation of the term of protective action of masks are given in table. 6. The calculations were based on the assumption that the maximum penetration rate at which operation is prohibited is - 25%.

Table 5. Results of calculating the term of the protective effect of masks

Fabric name	Penetration rate in the final term, K	Initial penetration rate, K_0	Protective action time, h
Velor	13.9	25	6.9
Wool	14.5		6.2
Two-thread cloth	9.7		12.9
Tricotine	12.8		8.3
Jersey	15.8		5.5
Frieze	19.3		2.8

Atlas	11.8		9.6

The obtained values of the penetration rate of protective masks correspond to the first class of protection of filter respirators, the penetration coefficient of the test aerosol, which in accordance with the requirements of the standard [12] should not exceed - 25%. Moreover, the period of protective masks, although it shows fairly good results, still has a certain uncertainty regarding the effect of air humidity, which can significantly reduce the obtained values and requires further research.

Therefore, studies show that certain tissues are able to provide protection against viruses transmitted by droplets. However, we emphasize that the overall protective effectiveness of the protective mask also depends on its design. Especially from the tightness to the face. This is a rather difficult task, which the manufacturers of filter respirators are gradually solving, due to the manufacture of special frames with variable geometry, which would take into account the anthropometric features of the faces. To increase the protective effectiveness of fabric masks, we can at least improve the seals at the points of contact with the face using, for example, polyurethane seals. In addition, these calculations were performed based on the performance of light work by the person, when the person makes no more than 8-10 cycles of inhalation and exhalation. Whereas the increase in the severity of the work will lead to the increase in the air consumption, and therefore it is necessary to carry out new calculations to clarify the period of the protective action.

The main result of the study is to establish the possibility of using conventional fabrics for the manufacture of protective masks, as evidenced by the identified relationships between their parameters: fiber diameter, packing density and thickness and performance properties of protective masks pressure drop and penetration rate

Conclusions

As a result of the experimental study to determine the main performance properties of fabrics: breathing resistance, penetration rate and resistance to dust, it was found that out of the twenty-two samples tested, only eight can be used for the manufacture of protective masks, since their characteristics are able to provide a sufficient level of protection from minimal physiological impact on human (wool, two-thread cloth, velor, tricotin, jersey, frieze and satin).

Theoretical calculation of the main indicators of protective masks, which can be made of these fabrics, based on experimental data allowed to make their compliance with the first class of protection according to the requirements of the standard [12].

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