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Original article

Testing filter elements for gas masks

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INFORMATION

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ABSTRACT

Contemporary threats to the natural environment due to atmospheric aerosols, including biological ones, are presented. The filtration process and practical solutions for the protection of the respiratory system against aerosols are characterized. The paper presents the results of tests on a flat filter card-board and a filter used in military gas filters for gas masks.

KEYWORDS

atmospheric aerosols, respiratory protection, filtration

Introduction

Civilization development is not only a modern boon, but also a great threat to man and his natural environment. The risk of civilization diseases is growing rapidly, which certainly include allergic diseases, asthma, and diseases of the upper and lower respiratory tract, which are more and more frequent. Most of the substances (both chemical, biological, and neutral) causing negative effects in the human body are found in the surrounding air. These can be toxic gases and dusts containing bacteria, viruses, fungi, and a wide range of elements and chemical compounds (organic and inorganic). The main route for the entry of toxic substances into the human body is the respiratory tract [1-3].

The main threat is dust, the high concentrations of which in the atmospheric air are one of the main environmental factors that have a detrimental effect on the health of the population, especially in relation to respiratory and cardiovascular diseases [4].

Particulate matter is a mixture of solid particles and liquid droplets remaining in the air. These molecules contain various components such as sulfur, organic compounds (e.g., polycyclic aromatic hydrocarbons), heavy metals, dioxins, and allergens (such as pollen and fungal spores). PM10 dust contains particles with a diameter smaller than 10 µm, while fine PM2.5 dust contains particles with a diameter smaller than 2.5 µm [5].

The harmfulness of dust to the health of exposed persons is closely related to the size and chemical composition of the grains. Fine dust with a diameter below 2.5 µm is the most dangerous. It reaches the alveoli and even penetrates into the blood vessels and from there into the bloodstream; hence, it is harmful both to the respiratory system and to the circulatory system. Larger dust grains can cause inflammation of the conjunctiva and the mucosa of the nose and throat. Exposure to high concentrations of dust may aggravate the symptoms of lung disease, various allergic diseases (asthma, eczema, hay fever, conjunctivitis), heart diseases (increased blood clotting, arrhythmias), and increase the susceptibility to respiratory infections. The carcinogenic effect cannot be excluded [6-8].

The SARS-CoV-2 coronavirus is the bane of recent months. The virus is most often transmitted by airborne droplets, i.e., when sneezing, coughing, etc. It can cause aerosol infections, i.e., indirectly and by settling on particles of dust, etc.

If the virus is transmitted mainly by droplets, which suggests that despite its very small size (the size of the virus particles has been estimated at 100 to 120 nm [9]), the carrier (droplet, dust, contamination) on which it is transported can exceed 0.2 μm [10; 11]. It means that the “carrier + virus” element can be effectively stopped by a suitable filter.

1. The filtration process

Aerosol filtration (dedusting) is a process leading to the permanent separation of the fragmented solid phase (dust) from the gas carrying (transporting) this phase. The following phases can generally be distinguished in filtration (dedusting) processes:

- *shaping the movement* of gas and dust grains,
- *coagulation*, namely, joining individual, small grains into groups, i.e., creating elements with a mass and dimensions greater than the mass and dimensions of the single grains,
- *separation* understood as permanent splitting dust from gas,
- *evacuation and disposal* of separated dust.

The filtration process takes place on the filtration partition, which can be fibrous or granular, loose or compact. The amount of impurities and the filtration mechanism used determine whether surface or depth filtration takes place at the partition. Besides, the particle sizes and the clearances in the filter partition or the pores if it is a porous medium are significant.

1. Surface filtration (Fig. 1a) takes place in the case of a significant amount of pollution in the form of solid particles contained in the filtered air. A layer of sediment (impurities) then forms on the partition, which then takes part in the filtration process. Over time, the layer grows, and so does the resistance to airflow through the partition.
2. Depth filtration (Fig. 1b), also known as volumetric filtration, occurs when there is a small number of solid particles that are either retained on the filtration screen or penetrate it. Then, no clear layer of sediment can be distinguished.

Depth filtration is much more common in air conditioning and ventilation. However, on some filters, mainly exhaust ones, and filters from local exhausts in heavily polluted rooms or rooms in which quite large particles are emitted, surface filtration is also noticeable.

The following filtering methods are typically used in air purification devices:

- mechanical – consisting in retaining impurities on various filtration materials, the so-called partitions,
- energetic – consisting in the separation of pollutants with the use of magnetic, electric, gravitational, centrifugal fields etc.,
- mechanical and energetic [13].

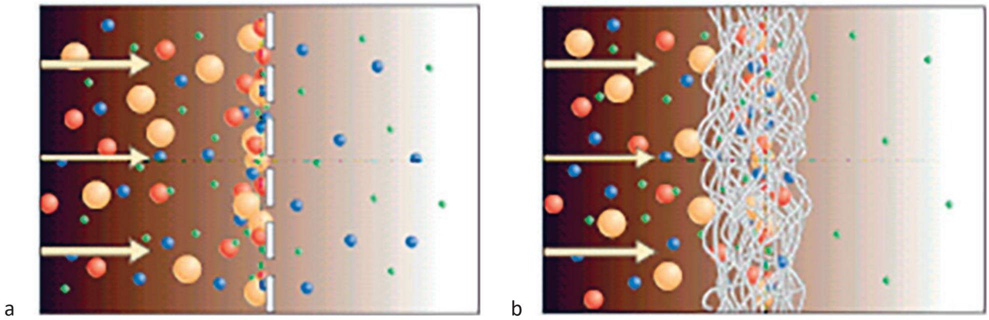

Fig. 1. Filtration: a – surface, b – depth (volumetric)
Source: [12].

The most famous phenomenon used in filtration is the sieve phenomenon. The sieve has been used by people in households to screen various loose materials since time immemorial. However, it is possible to take advantage of this phenomenon only as long as the dirt particles have a larger diameter than the free cross-section between the fibers.

The basic mechanisms used in air filtration processes are:

– diffusion,
– hooking,
– gravitational deposition,
– inertial collision,
– electrostatic interaction,
– sieve effect.

The mechanism of separating aerosol particles on the filter layer is shown schematically in Figure 2.

2. Practical solutions

Protection of the respiratory tract against dusts and aerosols is performed with the use of masks, half-masks, and respirators equipped with appropriate cleaning elements [14; 15]. Figure 3 shows a list of the protective measures used, and Figure 4-8 – the cleaning elements.

The filtration efficiency is determined in relation to standard aerosols, i.e., sodium chloride and paraffin oil mist. Depending on the filtering efficiency, filter elements are divided into three protection classes:

– class 1 – (marked as P1) – 80% filtration efficiency – used for protection against low toxicity solid particles for which TLV[1] ≥ 2 mg/m³,

[1] The threshold limit value (TLV) is the weighted average value of the concentration, the impact of which on the employee during the 8-hour daily and average weekly working time, specified in the Act of June 26, 1974 – Labor Code [Ustawa z dnia 26 czerwca 1974 r. Kodeks pracy (Dz. U. 1974 Nr 24, poz. 141)], during the period of his professional activity does not should cause negative changes in his health and the health of his future generations. Regulation of the Minister of Family, Labor, and Social Policy of June 12, 2018, on the highest allowable concentrations and intensities of factors harmful to health in the work environment, Journal of Laws, item 1286 [Rozporządzenie Ministra Rodziny, Pracy i Polityki Społecznej z dnia 12 czerwca 2018 r. w sprawie najwyższych dopuszczalnych stężeń i natężeń czynników szkodliwych dla zdrowia w środowisku pracy (Dz. U. 2018, poz. 1286)].

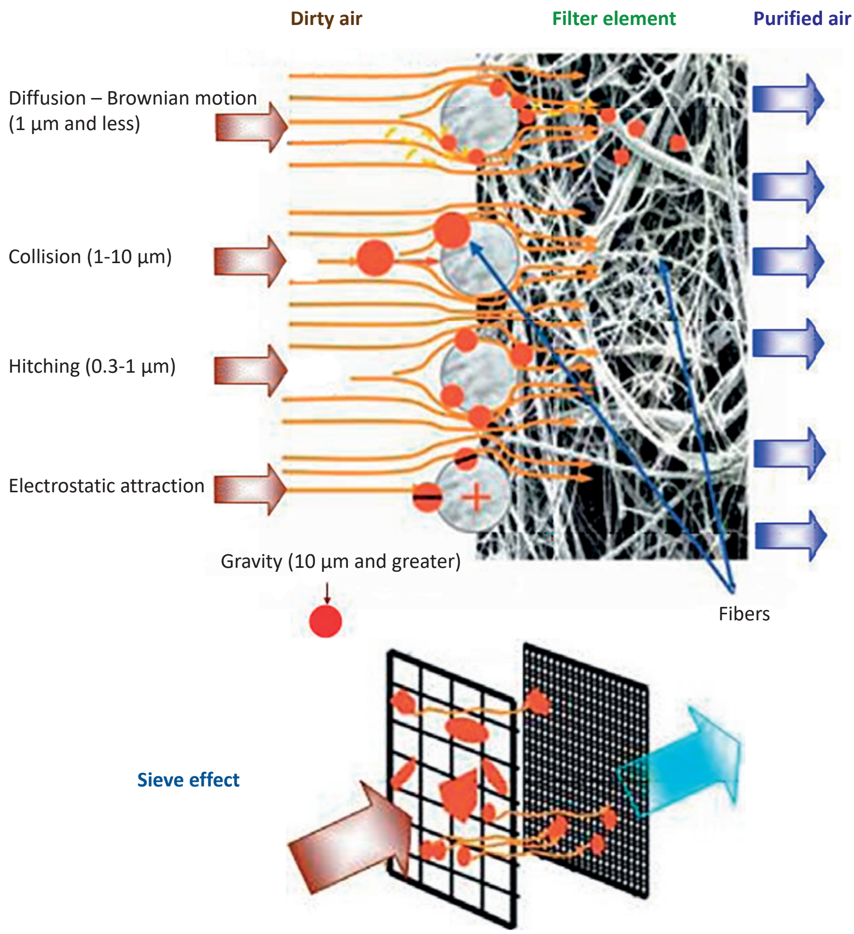

Fig. 2. Basic mechanisms of filtration
Source: [12].

- class 2 – (marked as P2) – 94% filtration efficiency – used for protection against solid and liquid particles of low and medium toxicity for which TLV ≥ 0.05 mg/m³,
- class 3 – (marked as P3) – 99.95% filtration efficiency – used for protection against high toxicity solid and liquid particles for which TLV < 0.05 mg/m³ [21].

According to of PN-EN 149 + A1:2010 Standard, depending on the effectiveness of filtering, filtering half masks are divided into three protection classes:

- class 1 – (marked as FFP1) – 80% filtration efficiency – used to protect against low toxicity solid and liquid particles for which TLV ≥ 2 mg/m³, provided that the maximum concentration is up to 4×TLV,
- class 2 – (marked as FFP2) – 94% filtration efficiency – used to protect against solid and liquid particles of low and medium toxicity for which TLV ≥ 0.05 mg/m³, provided that the maximum concentration is up to 10×TLV,
- class 3 – (marked as FFP3) – filtration efficiency 97% – used for protection against highly toxic solid and liquid particles for which TLV < 0.05 mg/m³, provided that the maximum concentration is up to 20×TLV [22].

Fig. 3. General structure (composition) of air purifying elements: 1 – full-face filtering mask, 2 and 3 – half mask, 4 – combined filter, 5 – combined filter components, 6 – pollen filter components, 7 – pollen filter cartridge
Source: Own study based on [16].

Fig. 4. Exchangeable P1, P2, and P3 class filter cartridges (comment below) for half masks
Source: [17].

Fig. 5. Exchangeable P3 class filter for the mask (comment below)
Source: [18].

Fig. 6. BIO-1 FFP3 half mask (comment below)
Source: [19].

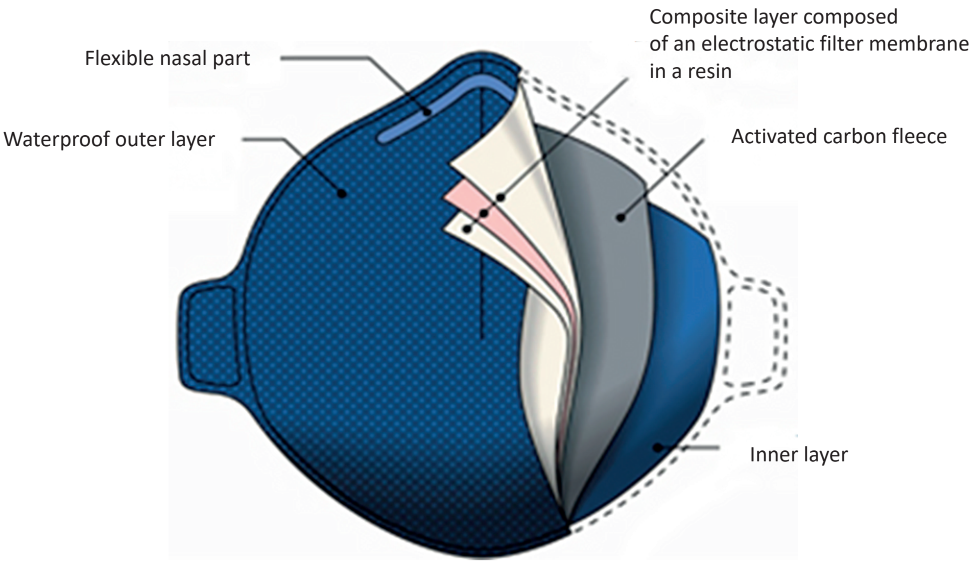

Fig. 7. BIO half mask with degradation of biological agents
Source: [20].

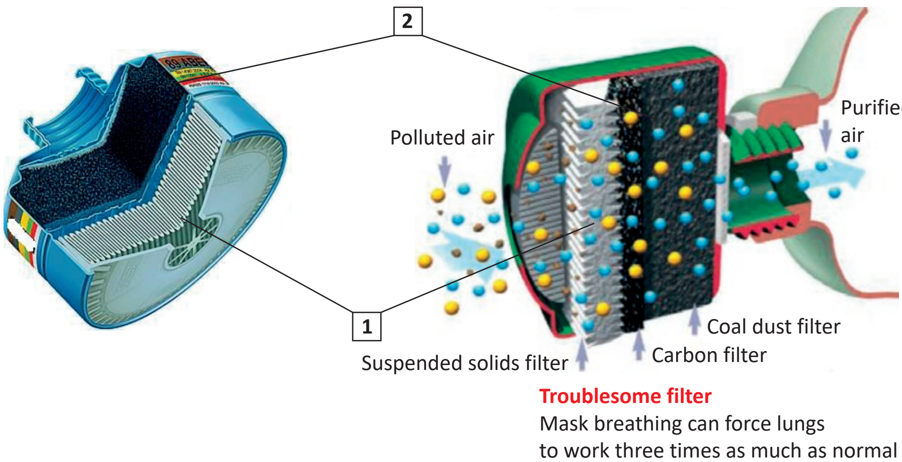

Fig. 8. General scheme of the combined filter construction: 1 – filter element, e.g., P3 class (HEPA class for the Polish Armed Forces), 2 – sorption cartridge
Source: [12].

The selection of respiratory protection measures should begin with hazard identification. It is necessary to identify air pollutants occurring or likely to arise at individual workplaces and determine their impact on the human body. In the absence of documented TLV for bio-aerosols, it is not possible to apply the standard procedure for selecting filtering equipment, consisting in the selection of protection class to the multiplicity of exceeding the permissible value of aerosol concentration. For this reason, guidelines for the selection of the protective class of filters and filtering half masks used for protection against bio-aerosol have been developed depending on the particle size and occupational risk group, in which the following was determined:

– for bio-aerosols, the particle size of which exceeds 1 μm and belongs to the 1st risk group – low efficiency half masks – FFP1 or P1 filters completed with half masks or combined filters,
– for bio-aerosol, the particle size of which is in the range of 0.5 ≤ d < 1 μm and belongs to the 1st or 2nd risk group – medium efficiency half masks – FFP2 or P2 filters completed with half masks or combined filters,
– for bio-aerosol, the particle size of which is in the range of 0.3 ≤ d < 0.5 m and belongs to the 3rd risk group – FFP3 respirators with the highest efficiency or a P3 filter completed with half masks or combined filters [23; 24].

3. Penetration testing through filter materials

The Polish Standard PN-EN 143:2004 specifies the basic protective parameter, namely the filtration efficiency determined by its penetration, which should not exceed the values given in Table 1.

The Polish Standard PN EN 1822-1:2009 provides the basic concepts of filtration:
– penetration – the ratio of the number concentration of particles downstream of the filter to the concentration upstream of the filter,
– efficiency – the ratio of the number of particles retained in the filter to the number of particles flowing to the filter,
– fractional efficiency – efficiency for particles of a given diameter. Effectiveness values presented as a function of dimensions (with given diameters give a fractional efficiency curve),
– EPA filter (Efficient Particulate Air filter) – effective air filter class from E10 to E12 – Table 2,
– HEPA filter (High Efficient Particulate Air filter) – highly efficient air filter of H13 – H14 classes – Table 2,
– ULPA filter (Ultra Low Penetration Air filter) – air filter with very low penetration of U15-U17 classes – Table 2,
– most penetrating particle size (MPPS) – the particle size for which the fractional filtration efficiency curve reaches a minimum.

The Polish Standard PN-EN 143:2004 presents the methodology of testing a flat filter material with the use of a polydisperse test aerosol.

Table 1. Filter penetration – maximum value according to PN-EN 143:2004

Filter class	Maximum filter penetration %	
	Sodium chloride test at the flow of 95 l/min	Paraffin oil mist test at the flow of 95 l/min
P1	20	20
P2	6	6
P3	0.05	0.05

Source: [21].

Table 2. EPA, HEPA, ULPA filters classification

Filter group	Filter class	Integer value		Local value	
		efficiency [%]	penetration [%]	efficiency [%]	penetration [%]
E (EPA)	E10	≥ 85	≤ 15	–	–
	E11	≥ 95	≤ 5	–	–
	E12	≥ 99.5	≤ 0.5	–	–
H (HEPA)	H13	≥ 99.95	≤ 0.05	≥ 99.75	≤ 0.25
	H14	≥ 99.995	≤ 0.005	≥ 99.975	≤ 0.025
U (ULPA)	U15	≥ 99.9995	≤ 0.0005	≥ 99.9975	≤ 0.0025
	U16	≥ 99.99995	≤ 0.00005	≥ 99.99975	≤ 0.00025
	U17	≥ 99.999995	≤ 0.000005	≥ 99.9999	≤ 0.0001

Source: [25].

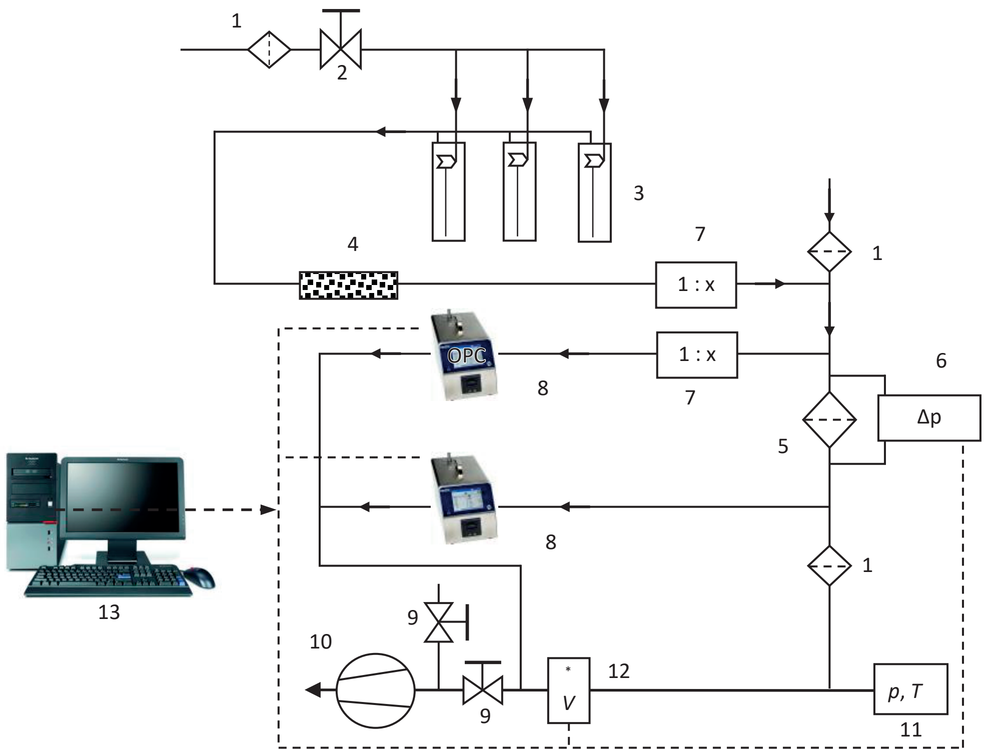

Fig. 9. Stand for testing the distribution and number concentration of aerosol particles before and after the tested filter material with the use of polydisperse aerosols: 1 – filter, 2 – pressure reducing valve, 3 – nozzle sprayer, 4 – neutralizer, 5 – holder of the tested filter material, 6 – flow resistance measuring device, 7 – dilution system, 8 – optical particle counter, 9 – needle valve, 10 – vacuum pump, 11 – instruments for measuring absolute pressure, temperature and relative humidity, 12 – device for measuring the volume flow, 13 – computer for controlling and storing data
Source: [12].

The scheme of the measuring stand is shown in Figure 9. Optical counters were used to determine the distribution and number concentration of aerosol particles before and after the tested filter material.

When testing with a test aerosol, it was also necessary to adjust the numerical concentration of the test aerosol particles to the appropriate measuring range of the particle counter, if necessary by adding a dilution system, using devices to count and separate the particles according to their size.

Table 3 shows the test results for a sample of a flat filter material, and Table 4 shows the calculated values of the average penetration and filtration efficiency. Figure 10 shows the penetration values, and Figure 11 shows the filtration efficiency with the determination of the most penetrating particle size (MPPS).

In order to increase the contact surface, the filter material (filter paper) is specially folded. In the production process, the filter element is automatically folded, stiffened, and sealed,

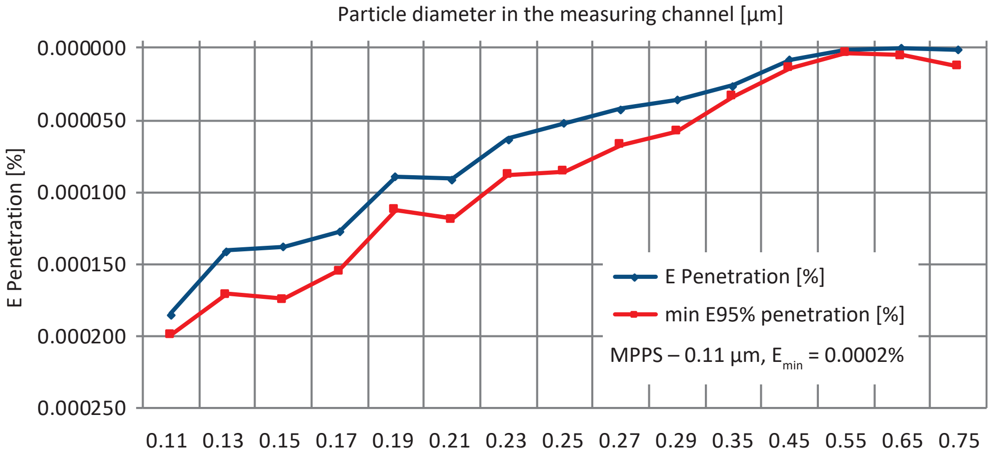

Fig. 10. Penetration values for flat filtering material
Source: Own study.

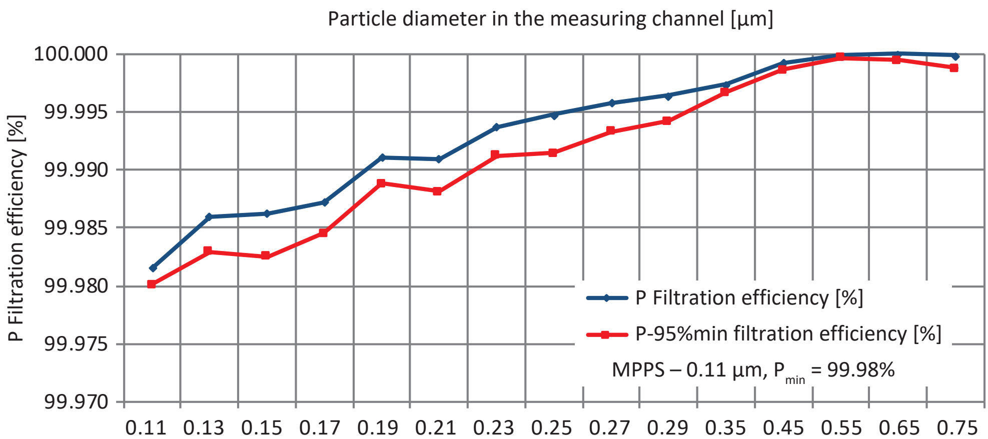

Fig. 11. Values of filtration efficiency for flat filter material
Source: Own study.

Table 3. Test results of flat filter material

Number of counts in the channel (Dilution: *10000)					
Counter before:					
d [µm]	**measure-ment 1**	**measure-ment 2**	**measure-ment 3**	**measure-ment 4**	**mean**
0.11	54430	55110	54780	54773	54773
0.13	28950	30030	29550	29510	29510
0.15	17090	17240	17180	17170	17170
0.17	12980	13150	13230	13120	13120
0.19	11130	11460	11250	11280	11280
0.21	5674	5814	5835	5774	5774
0.23	5645	5650	5739	5678	5678
0.25	5168	5337	5399	5301	5301
0.27	4690	4813	4814	4772	4772
0.29	5012	5050	4962	5008	5008
0.35	25340	25690	25400	25477	25477
0.45	17810	18270	18020	18033	18033
0.55	25710	25950	26360	26007	26007
0.65	7402	7730	7443	7525	7525
0.75	3119	3274	3164	3186	3186
Counter after:					
0.11	999	991	1039	1010	999
0.13	386	393	441	407	386
0.15	222	222	264	236	222
0.17	154	170	178	167	154
0.19	96	100	105	100	96
0.21	43	58	56	52	43
0.23	36	28	43	36	36
0.25	35	22	26	28	35
0.27	20	25	15	20	20
0.29	20	16	18	18	20
0.35	73	64	62	66	73
0.45	17	11	14	14	17
0.55	4	5	1	3	4
0.65	0	0	0	0	0
0.75	0	0	1	0	0

Effective area of the tested sample of filter material: A – 100 cm², flow rate 95 l/min., flow resistance: Δp = 383 Pa.

Source: Own study.

and the penetration of each element is automatically checked. For research purposes, tests on the folded filter material were carried out. The test results are presented in Tables 5 and 6 and in Figures 12 and 13.

Table 4. Mean values of penetration and average filtration efficiency

	particle diameter [µm]					
	0.11	**0.13**	**0.15**	**0.17**	**0.19**	**0.21**
E penetration [%]	0.000184	0.000140	0.000137	0.000128	0.000089	0.000091
min E95% penetration	0.000199	0.000171	0.000174	0.000154	0.000112	0.000119
filtration efficiency	99.98157	99.98595	99.98626	99.98725	99.99111	99.99094
minimum filtra-tion efficiency	99.98009	99.98292	99.98256	99.98456	99.98881	99.98814
	particle diameter [µm]					
	0.23	**0.25**	**0.27**	**0.29**	**0.35**	**0.45**
E penetration [%]	0.000063	0.000052	0.000042	0.000036	0.000026	0.000008
min E95% penetration	0.000088	0.000086	0.000067	0.000058	0.000033	0.000013
filtration efficiency	99.993718	99.994781	99.995809	99.996406	99.997396	99.999224
minimum filtra-tion efficiency	99.991220	99.991447	99.993297	99.994202	99.996686	99.998654
	particle diameter [µm]					
	0.55	**0.65**	**0.75**			
E penetration [%]	0.0000013	0.0000000	0.0000010			
min E95% penetration	0.0000035	0.0000052	0.0000124			
filtration efficiency	99.99987	100	99.9999			
minimum filtra-tion efficiency	99.99965	99.99948	99.99876			

Source: Own study.

Table 5. Test results of flat filter material

Number of counts in the channel (Dilution: *10000)						
Counter before:						
d [µm]	measure-ment 1	measure-ment 2	measure-ment 3	measure-ment 4	measure-ment 5	Mean
0.11	68190	68220	63970	61970	69260	66322
0.13	34860	34220	30370	28270	32260	31996
0.15	17860	18370	15690	14770	16850	16708
0.17	13100	12980	11770	11280	12520	12330
0.19	11210	11030	10050	10060	10860	10642
0.21	5910	5757	5455	5336	5657	5623
0.23	5699	5624	5247	5102	5254	5385
0.25	5382	5472	5050	4883	5179	5193
0.27	4966	4983	4628	4450	4723	4750
0.29	5113	5046	4883	4623	4841	4901
0.35	26470	26670	24280	23650	24620	25138
0.45	19210	18780	17540	16880	17540	17990
0.55	29000	28020	25840	24040	25910	26562
0.65	9587	9598	8491	8029	9084	8958
0.75	4533	4479	4107	3991	4288	4280
Counter after:						
0.11	1467	1537	1169	983	1073	1245.8
0.13	628	676	474	427	422	525.4
0.15	351	338	260	206	195	270
0.17	237	234	167	118	126	176.4
0.19	164	141	107	83	74	113.8
0.21	66	57	45	37	28	46.6
0.23	40	48	37	24	25	34.8
0.25	28	37	25	23	17	26
0.27	27	30	18	8	14	19.4
0.29	32	26	14	16	14	20.4
0.35	63	70	47	42	42	52.8
0.45	19	13	9	9	7	11.4
0.55	2	4	4	2	1	2.6
0.65	1	0	0	1	0	0.4
0.75	0	1	0	0	1	0.4

Effective area of the tested sample of filter material: A – 100 cm², flow rate 95 l/min., flow resistance: Δp = 410 Pa.

Source: Own study.

Table 6. Mean penetration values and average filtration efficiency

	Particle diameter [µm]					
	0.11	**0.13**	**0.15**	**0.17**	**0.19**	**0.21**
E penetration [%]	0.000188	0.000164	0.000162	0.000143	0.000107	0.000083
min E95% penetration	0.000248	0.000235	0.000242	0.000218	0.000162	0.000123
filtration efficiency	99.98122	99.98358	99.98384	99.98569	99.98931	99.99171
minimum filtration efficiency	99.97517	99.97649	99.97577	99.97822	99.98381	99.98773
	Particle diameter [µm]					
	0.23	**0.25**	**0.27**	**0.29**	**0.35**	**0.45**
E penetration [%]	0.0000646	0.0000501	0.0000408	0.0000416	0.0000210	0.0000063
min E95% penetration	0.0000939	0.0000718	0.0000687	0.0000655	0.0000103	0.0000103
filtration efficiency	99.99354	99.99499	99.99592	99.99584	99.9979	99.99937
minimum filtration efficiency	99.99061	99.99282	99.99313	99.99345	99.99897	99.99897
	Particle diameter [µm]					
	0.55	**0.65**	**0.75**			
E penetration [%]	0.000001	0.000000	0.000001			
min E95% penetration	0.000002	0.000001	0.000003			
filtration efficiency	99.9999	99.99996	99.999907			
minimum filtration efficiency	99.99982	99.99987	99.999729			

Source: Own study.

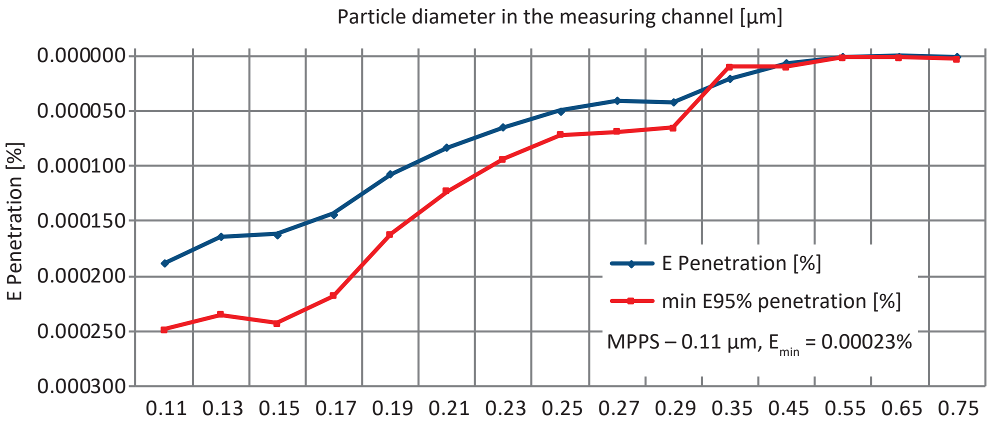

Fig. 12. Penetration values for the pleated filter material
Source: Own study.

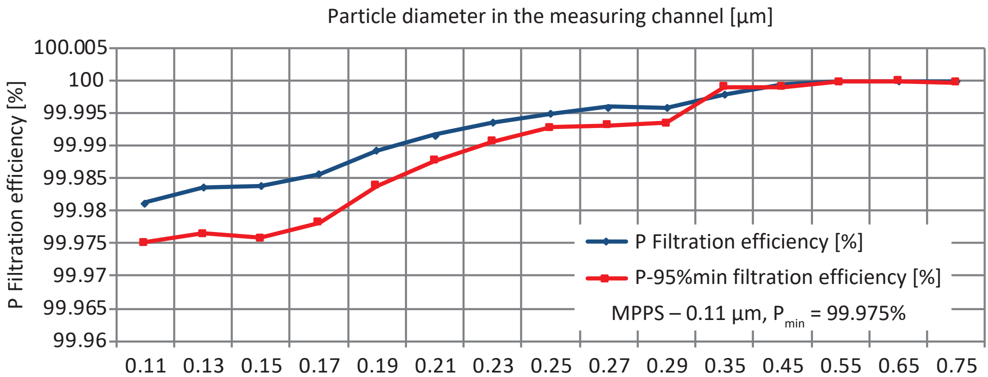

Fig. 13. Values of filtration efficiency for the pleated filter material
Source: Own study.

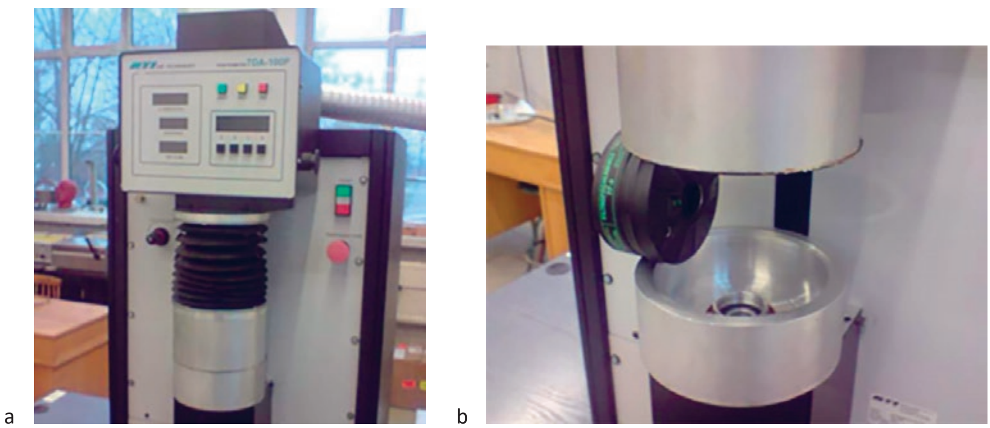

Fig. 14. Stand for testing the penetration and breathing resistance of combined filters for gas masks: a – a camera; b – a handle

Source: Own collection.

In the acceptance tests of filters and combined filters, penetration and flow resistance are assessed. The research is carried out on special testers. The exemplary tester is shown in Figure 14, and the results of FP-6 combined filters are presented in Table 7.

Table 7. Results of DEHS aerosol penetration and respiration resistance of FP-6 combined filters

Symbol of the tested combined filter [%]	Penetration P [%]	Maximum breathing resistance [Pa] at the flow of 95 dm³/min
FP/60/08	> 0.001	330
FP/64/08	> 0.001	370
FP/80/08	> 0.001	350
FP/82/08	> 0.001	360
FP/100/08	> 0.001	340
FP/123/08	> 0.001	370
FP/160/08	> 0.001	350
FP/185/08	> 0.001	380
FP/213/08	> 0.001	340
FP/276/08	> 0.001	340

Source: Own collection.

Summary

The problem of protecting the respiratory tract against atmospheric aerosols is becoming more and more important. Atmospheric contamination can be caused by dusts that contain very toxic chemicals, radioactive isotopes, and, as we can see now, very infectious biological substances.

Respiratory protection is a difficult process. Personal protective equipment is one of such technical solutions and it should be properly constructed, tested, and approved for use to fulfill its protective function in the best possible way Personal protective equipment of this type must not only ensure adequate efficiency in retaining dust and microorganisms in the filter material, but also should not themselves constitute a source of infection when used. It means that, in addition to very good protective properties, these agents must meet many operational parameters, such as adaptability and low flow resistance (breathing).

Requirements for personal protective equipment for workers are listed in Directive 89/686/EEC/ and in national regulations. According to the rules set out in the Directive, the CE marking confirms that the product meets the essential requirements. Unfortunately, the Directive does not specify the requirements for this type of equipment as a means of universal use and, for example, for the Armed Forces.

This article presents the results of filtration efficiency tests according to the requirements of PN-EN 143:2004. The research aimed to select an appropriate filter material for military filters and test the stand for determining the distribution and number concentration of aerosol particles before and after the tested filter material with the use of polydisperse aerosols. The tested filter material was not the target one, and the presented findings are one of many laboratory tests. The obtained results of penetration tests for flat filter material E_{min} = 0.00023% for the most penetrating particle MPPS = 0.11 µm and E_{min} = 0.0002% for corrugated filter material prove that the use of HEPA filter cartridges protects users against respirable dust and biological aerosols. The test results of ready FP-6 combined filters show that they meet the requirements of PN-EN 143:2004 Standard and NO-42-A205:2009 Standard Defense [26].

Conclusions

1. There is a real threat to the human body through the respiratory tract with dust and biological aerosols.
2. The respiratory system protection measures should be secured with the protective measures of the effectiveness specified in the normative documents. For air aerosols, this will be penetration.
3. Combined filters used in military respiratory protection measures have a very good protective effect. The measured penetrations of the test substances through the materials and filter packs are significantly higher than required.

Acknowledgement

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Conflict of interests

The author declared no conflict of interests.

Author contributions

The author contributed to the interpretation of results and writing of the paper. The author read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

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Badania elementów filtracyjnych do masek przeciwgazowych

STRESZCZENIE Przedstawiono współczesne zagrożenia środowiska przyrodniczego aerozolami atmosferycznymi, w tym biologicznymi. Scharakteryzowano proces filtracji oraz rozwiązania praktyczne stosowane w ochronie układu oddechowego przed aerozolami. Przedstawiono wyniki badań płaskiego kartonu filtracyjnego i filtra stosowanego w wojskowych filtropochłaniaczach do masek przeciwgazowych.

SŁOWA KLUCZOWE aerozole atmosferyczne, ochrona układu oddechowego, filtracja

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