

Clogging of Filtering Material Systems Used for Disposable Respirators

Jacek Krzyżanowski

Filter-Service, Poland

Katarzyna Majchrzycka

Centralny Instytut Ochrony Pracy, Poland

The article shows the problem of clogging in connection with the parameters of filtering materials used in respiratory protective equipment. The results of investigations of airflow resistance changes during the depositing of dust inside the filtering material are presented. The configuration of layers differing in mass per unit area and the number of layers, were taken into consideration. For each configuration, the clogging abilities and the changes of airflow resistance as a reason of loading with dust were assessed. The analysis of tested materials confirms the hypothesis that there is an important coincidence between the properties of the material used in filtering equipment and the clogging coefficient. The results show that the filter should have a layered structure and that the outer layer should be made of a nonwoven of relatively high surface density.

respiratory protective equipment filtering material filtering half-masks
surface density clogging breathing resistance

1. INTRODUCTION

If the respiratory protective device is to perform its protective function well, it should be characterized by a great capacity to stop airborne contaminants (Brown, 1980; Brown, 1995; Dorman, 1966; Pich, 1966), by depositing and accumulating them in the filtering material. This phenomenon is accompanied by a simultaneous increase in the resistance of airflow through the filtration material due to an increase in the mass of the accumulated dust. The accumulation of dust in the filtering material causes an increase in breathing resistance until breathing becomes so difficult that the device used has to be replaced with a new piece. Such a situation is especially typical of the mining industry, where concentration in the surrounding atmosphere is high (Brown, Wake, Gray, Blackford, & Bostock, 1988), and the climatic conditions aggravate this phenomenon.

The process of dust accumulation in the filtering material—called clogging—is so fast that the device operation time, limited by the highest permissible airflow resistance,

is extremely short and results in the necessity to repeatedly replace the respirator during one shift. Hence, attempts are made at improving filtering materials in such a way that their capacity to stop large amounts of dust particles increases with simultaneous low rate of increase in airflow resistance. On the one hand, the rate of filtering material clogging is closely related to dust parameters (Brown, 1993; Gradoń & Payatakes, 1982; Payatakes & Gradoń, 1980; Ramarao & Chi Tien, 1988), dust concentration in the air, and the type of work done under these conditions. On the other hand, it depends on the filter parameters.

2. CLOGGING OF DISPOSABLE RESPIRATORS

It has been found (Brown, 1995; Smissen, 1971, as cited in Brown, 1993) that uniform loading of the filter with dust, in such a way that its volume increases by 1%, will cause simultaneous doubling of resistance in the airflow. However, this is true only on the assumption that the filter is of the same thickness and the packing of dust is uniform. In practice, a considerably greater increase in breathing resistance is observed than that calculated on the basis of the theory. This phenomenon is affected by the actual size of dust particles found in the polluted air. The greater the amount of dust settled on the filtering material during its use, the greater interaction of the particles, which join to form dendrites (Brown, 1993; Gradoń & Payatakes, 1982; Payatakes & Gradoń, 1980). Electrical forces in the filtering material (Gradoń & Payatakes, 1982) cause a better distribution of dust particles in the filter structure, because the initiation of dendrites formation can take place at any point of the fibre. This has direct effect on the uniform distribution of particles around the fibre and collapsing dendrites (Brown, 1993), which results in a slower increase of the resistance to airflow through the material.

The structure itself of the filtering material has a direct effect on the possibility of an increase in the number of dendrites, because filters of an open structure and a low degree of fibre packing have greater free space in which dendrites are formed. They would have to grow to considerable sizes to seriously restrict the passage of the air through the filter (Shucoski, Geraci, Turner, & Cameron, 1984). At the same time, there is correlation between filtration efficiency and the rate of the clogging of filtering materials. A higher effectiveness of the layer means that the aerosol will be trapped by a smaller volume of the filter. It follows that the more loaded part of the filter becomes more effective (Brown, 1993; Dorman, 1966; Pich, 1966). The outer layer, which shows the greatest tendency to be clogged, is such a layer. Thus, it is highly probable that better particle-holding properties can be obtained by a proper selection of the structure of the filter itself. The layer filter can be made of such composite materials that the least effective part is exposed to dust first. Another variation of the layer filter is a filter made of a needled nonwoven fabric, but of a varied degree of packing so that the outer layer of the filter is looser and more open.

On the basis of the presented considerations, one can expect that it is possible to shape the structure of a filtering material in such a way that the respirator manufactured of this material can be used in a dusty environment for quite a long

time without excessive growth of breathing resistance. The aim of this investigation was to analyze the actual clogging properties of commercially available disposable antidust respirators and to reveal the main relations between the configuration of the filtering systems applied in the respirators and their ability to clog.

To express the ability to clog, we used a parameter called clogging coefficient, W_p . The clogging coefficient is measured in a laboratory dust chamber and it is defined as the ratio of the mass of the dust deposited in the filter until its airflow resistance has reached the value of 400 Pa, to the mass of 1.5 g.

3. TESTING MATERIAL

Ten different, commercially available disposable antidust half-masks with layer systems of different nonwovens were tested. Then, some other specially prepared systems of nonwovens were investigated. The systems consisted of different combinations of the following types of material:

1. polyester/polypropylene needled nonwoven of surface density
 - 1.1. 200 g/m²,
 - 1.2. 300 g/m²;
2. polypropylene melt-blown nonwoven of surface density
 - 2.1. 60 g/m²,
 - 2.2. 80 g/m²,
 - 2.3. 100 g/m²,
 - 2.4. 380 g/m²;
3. thermoplastic polypropylene/polyester nonwoven of surface density 20 g/m²,
4. separating polypropylene melt-blown nonwoven of surface density 100 g/m².

The tested combinations of the materials are presented in Table 1.

TABLE 1. Investigated Filtering Systems

Item	Filtering System	Number of Layers	Arrangement of Layers
1	A	3	1.2 + 2.2 + 3
2	B	3	1.1 + 2.3 + 3
3	C	2	1.1 + 2.4
4	X	4	1.2 + 4 + 2.1 + 3
5	I	3	1.1 + 2.1 + 3
6	II	4	1.1 + 4 + 2.1 + 3
7	III	4	1.2 + 4 + 2.1 + 3

Note.

- 1.1—polyester/polypropylene needled nonwoven of surface density 200 g/m²,
- 1.2—polyester/polypropylene needled nonwoven of surface density 300 g/m²,
- 2.1—polypropylene melt-blown nonwoven of surface density 60 g/m²,
- 2.2—polypropylene melt-blown nonwoven of surface density 80 g/m²,
- 2.3—polypropylene melt-blown nonwoven of surface density 100 g/m²,
- 2.4—polypropylene melt-blown nonwoven of surface density 380 g/m²,
- 3—thermoplastic polypropylene/polyester nonwoven of surface density 20 g/m²,
- 4—separating polypropylene melt-blown nonwoven of surface density 100 g/m².

4. EXPERIMENTS AND RESULTS

To measure the deposition of dust particles in filtering material, a special test rig for determining the dust-holding capacity of filters and filtering half-masks was constructed. It was designed on the basis of the method for determining clogging of respirators by coal dust (Comité Européen de Normalisation [CEN], 1990). A schematic diagram of the test rig is shown in Figure 1.

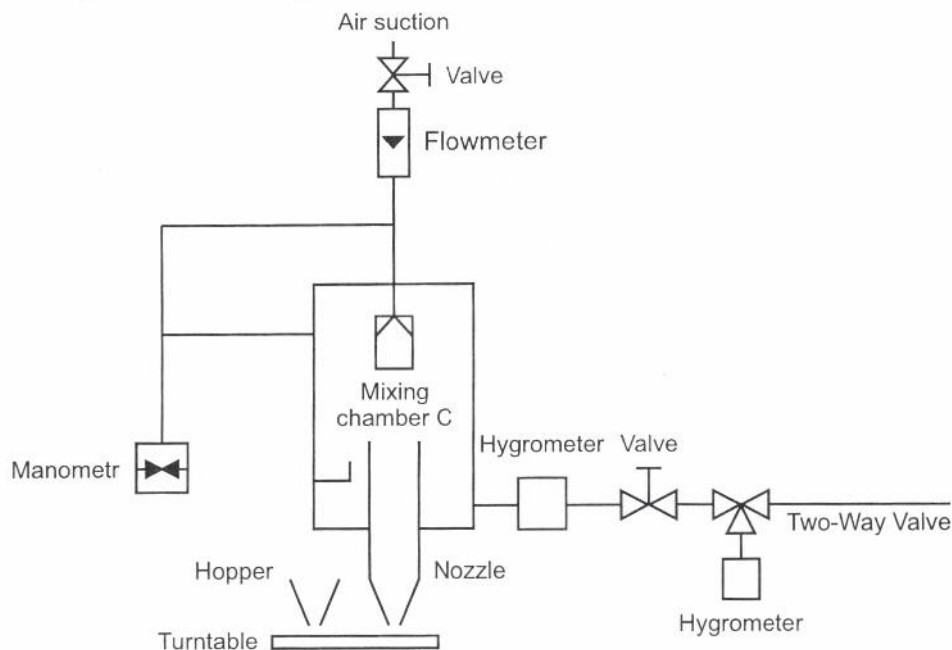


Figure 1. A schematic diagram of the test rig used for loading filters with dust.

The test method consisted in passing a test aerosol (silica dust) through the filter or half-mask and determining the mass of the dust that settled on the tested object. To calculate the clogging coefficient, the measurement was carried out until the resistance to airflow reached the value of 400 Pa. The concentration of dust in the measuring chamber was 110 mg/m^3 and the volume air rate through the whole active surface of the object was equal to $95 \text{ dm}^3/\text{min}$. The particle size distribution of the used silica dust is presented in Figure 2.

For each type of half-mask, the surface density of the whole material system as well as the surface density of the outer layer were determined by cutting a circle 50 mm in diameter and weighing it. The initial resistance to airflow was measured—in accordance with CEN (1991)—at the volume air rate through the whole active surface equal to $95 \text{ dm}^3/\text{min}$. Then, using the measuring rig shown in Figure 1, the clogging coefficient (W_p) of each half-mask was determined, according to the aforementioned definition of this coefficient. The dust concentration in the measuring chamber was 110 mg/m^3 . The measurement was completed when the airflow resist-

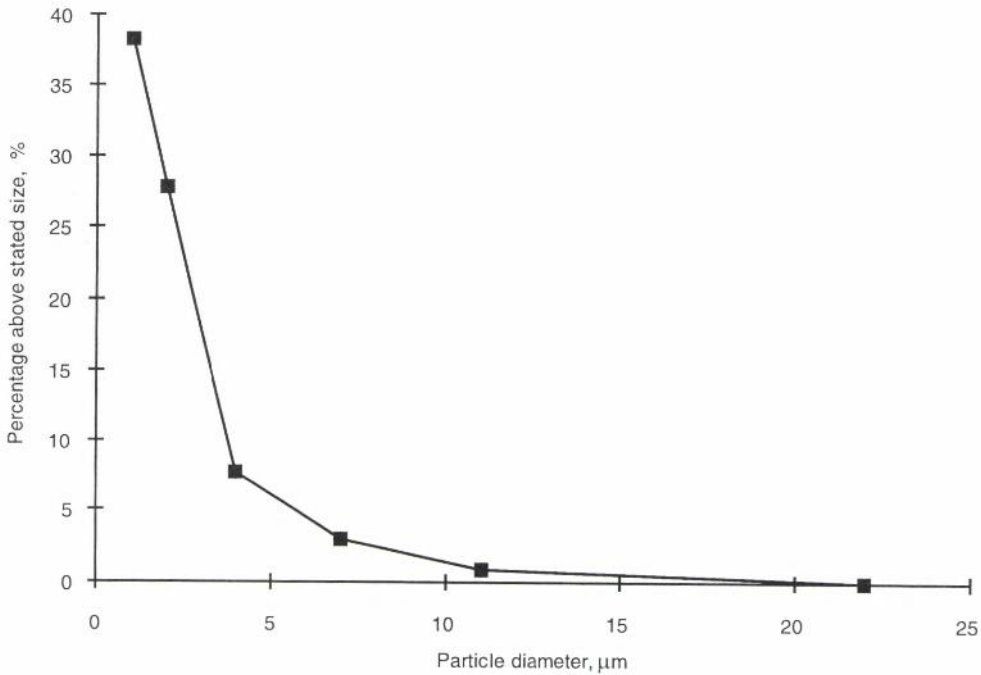


Figure 2. Particle size distribution of the silica dust used for loading filters.

ance reached the value of 400 Pa. For every type of respirator, the measurement were done on three samples and the average was calculated. The results are presented in Table 2.

TABLE 2. Disposable Filtering Half-Masks: Results of Measurements

Filtering Half-Mask	M_p of Outer Layer	Whole M_p	p (Pa)	W_p
A	19.5	270.0	82	0.66
B	164.5	546.8	133	0.76
C	20.9	224.0	67	0.87
D	220.0	350.0	123	1.44
E	275.0	335.0	103	2.16
F	169.0	434.5	76	1.32
G	144.6	360.5	121	1.24
H	139.6	329.6	98	0.90
I	136.8	325.0	25	2.13
J	45.9	466.4	25	2.50

Note. M_p —surface density (g/m^2), p —initial breathing resistance, W_p —clogging coefficient, which has been defined as $W_p = M/M_{\min}$, where, M —the amount of dust collected during testing until the resistance of the sample has reached a specified value, M_{\min} —the minimum mass of the dust that has to be collected for filtering half-masks (500 mg).

Three new samples of every type of considered respirators were then investigated for changes of airflow resistance during loading with dust. Before the test, the filtering half-masks were placed in the measuring chamber C (see Figure 1). The volume air rate through the tested sample was $95 \text{ dm}^3/\text{min}$. The dust concentration in the chamber was $110 \text{ mg}/\text{m}^3$. The measurement was completed when the airflow resistance of the sample reached the value of 350 Pa or after 200 min . During the measurement, the changes of the airflow resistance in time, resulting from the accumulation of the dust in the tested element were registered. The results of the experiment are presented in Figure 3.

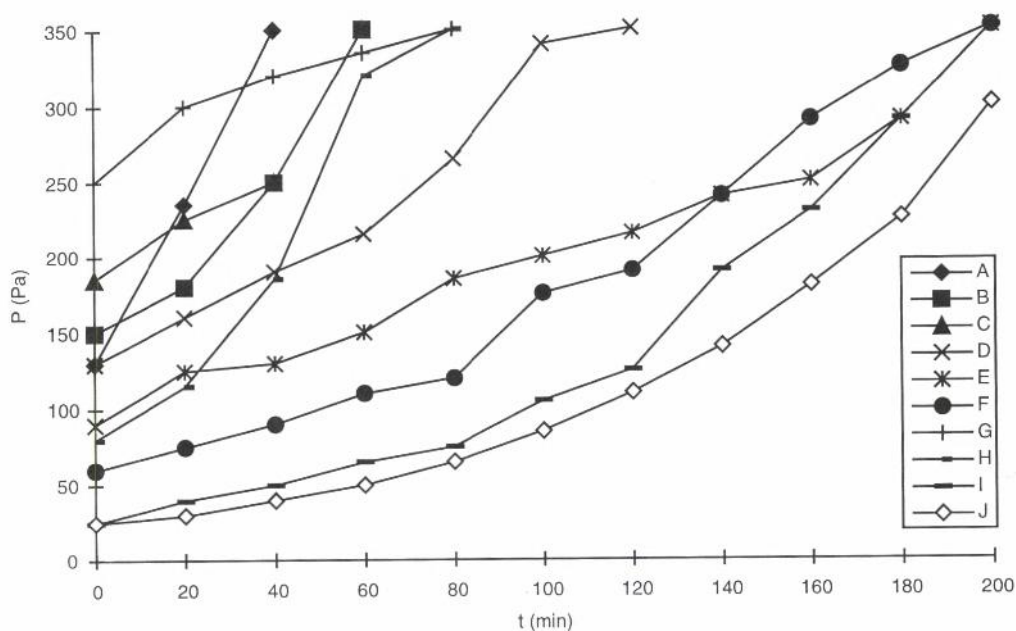


Figure 3. Changes of airflow resistance during the time of loading filtering half-masks with dust. Note. A—filtering half-mask A; B—filtering half-mask B; C—filtering half-mask C; ... J—filtering half-mask J.

At the first stage of investigation, filtering half-masks served as the testing material. The half-masks differed in protection class, shape, presence of the exhalation valve, and materials used for their production (the types of half-masks or their manufacturers cannot be revealed). Further research was undertaken on nonwoven layer systems made of filtering materials presented in Table 1: The first of the series of tests included items 1–4, the second one—items 5–7. Testing each system, the changes of airflow resistance during loading with dust were measured for each tested system. In both series of investigations, the surface density of the system as well as of the particular layers, initial airflow resistance, and the clogging coefficient were measured. In the second series, besides the already mentioned parameters, the masses of the dust deposited in particular layers were measured. The results of the first series of experiments are presented in Figure 4 and Table 3. The results of the second series of experiments are presented in Table 4.

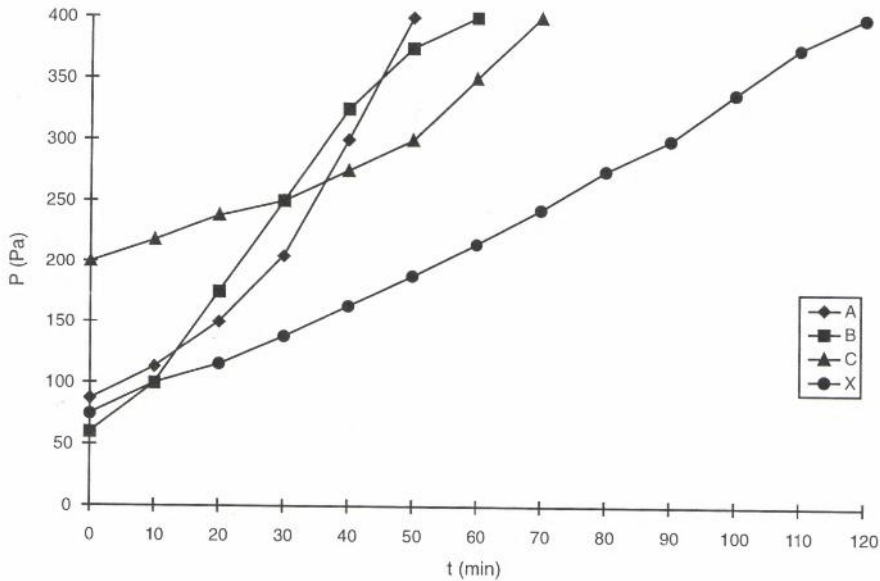


Figure 4. Changes in airflow resistance during the time of loading the first series of filtering systems with dust. Note. A—filtering system A; B—filtering system B; C—filtering system C; X—filtering system X.

TABLE 3. First Series of Filtering Systems: Results of Measurements

Filtering System	Number of Layers	M_p of Outer Layer	M_p of Main Filter	M_p of the Whole System	p (Pa)	W_p
A	3	265.0	84.6	369.6	87	0.76
B	3	231.4	105.0	356.4	60	0.76
C	2	188.6	379.1	567.7	200	1.33
X	4	265.0	60.0	445.0	75	2.28

Note. M_p —mass per unit area (g/m^2), p —initial breathing resistance, W_p —clogging coefficient, which has been defined as $W_p = M/M_{\min}$, where, M —the amount of dust collected during testing until the resistance of the sample has reached a specified value, M_{\min} —the minimum mass of the dust that has to be collected for filtering half-masks (500 mg).

TABLE 4. Second Series of Filtering Systems: Results of Measurements

Filtering System	Layers	Mass per Unit Area (g/m^2)			
		1	2	3	4
I	3	200	—	60	20
II	4	200	100	60	20
III	4	300	100	60	20

Note. 1—needled nonwoven, 2—separating nonwoven, 3—melt-blown electrostatic filtering material, 4—covering nonwoven.

TABLE 5. Dust Deposited in Different Layers of the Second Series of Filtering Systems

Symbol	p (Pa)	W _p	Dust-Holding Capacity (mg)			
			1	2	3	4
I	118	1.40	661	—	40	1
II	160	1.40	643	19	31	1
III	190	1.51	680	71	5	1

Note. 1—needled nonwoven, 2—separating nonwoven, 3—melt-blown electrostatic filtering material, 4—covering nonwoven. p—initial breathing resistance, W_p—clogging coefficient, which has been defined as $W_p = M/M_{min}$, where, M—the amount of dust collected during testing until the resistance of the sample has reached a specified value, M_{min}—the minimum mass of the dust that has to be collected for filtering half-masks (500 mg).

5. DISCUSSION

An analysis of the diagrams (Figure 3) illustrating the change of resistance to the airflow through the investigated element brought about by the deposition of dust on its surface has shown that the character of these changes is in most cases the same. For the group of half-masks of small dust-holding capacity, at an initial stage of measurement, there occurred a rapid increase in the airflow resistance due to the fast clogging of the half-mask. During the investigations of half-masks with good dust accumulation properties, the increase in airflow resistance was slower, which pointed to the capacity of the half-masks for a longer period of working under real conditions—the half-mask depicted by curve G (Figure 3) is an exception. Its shape is indicative of the fast clogging of the half-mask surface at the first stage of its usage, yet this process is decelerated to such an extent that the general rating of the dust-holding capacity expressed by the clogging coefficient W_p is greater than one, which is considered good. This half-mask differed radically from the others in its outer layer made of porous polyurethane foam. It allows penetration of dust particles into the layers located deeper and their better packing.

Half-masks depicted by curves A, B, C, and H are among the respirators whose clogging coefficient is less than one. The outer layer of these half-masks is made of smooth nonwoven. Two of them—half-masks A and C—have the same arrangement of layers, the only difference being that one of them has an exhalation valve. This difference results in different initial values of inhalation resistance. The half-mask without the valve, with a lower value of initial airflow resistance, presents better dust-cumulative properties. This result points to the effect of the size of the outer surface of the half-mask which, limited by the surface of the valve, has a poorer ability to accumulate dust. High initial airflow resistance of the half-mask with the same outer layer will also cause its faster clogging. Among the half-masks there is also the one denoted by curve B, with nonwoven as an outer layer, but of a greater surface density area than the half-mask mentioned further. Because of this, despite the limitation of the active surface by the exhalation valve as well as the great value of initial airflow resistance, its dust-cumulative properties are better than those of the half-mask denoted by symbol A.

Half-mask H, whose surface density of the outer layer is very close to that of half-mask B, but whose initial airflow resistance is considerably lower, shows better dust-depositing properties. However, as none of these half-masks presents good dust-depositing properties, which is shown by the value of the clogging coefficient below one, it should be stressed that smooth materials of low surface density are susceptible to fast clogging with dust particles and cannot be recommended as an outer layer of devices designed for use in places of high dust concentration.

The group of half-masks whose clogging coefficient points to better dust accumulation properties are the ones in which needled nonwoven, serving as an initial filter of considerable mass per unit area, constitutes the outer layer. In this group of tested devices, the effect of the volume of initial airflow resistance on the duration of the operation of the device under conditions of high dust concentration is also confirmed. This is so because with the outer layer of similar mass per unit area and the same raw material composition (half-masks F and D), the smaller value of initial airflow resistance for half-mask F was decisive for its longer operation time. This can be seen from a comparison of the shape of curves F and D. The analyzed group of half-masks marked E, for which the curve shape indicates a steady increase in breathing resistance during the use of the device, manifests the best dust-depositing properties. This design is characterized by a greater surface density of the outer layer than that of the previously mentioned one, whereas the relation of the surface density of the outer layer to the surface density of the whole half-mask points to a great percentage portion of this layer in relation to the whole mass of the half-mask.

The group of half-masks presented is characterized by the presence of the same arrangement of layers in the form of the outer—dust-depositing—layer and the filtration layer made from microfibres, placed directly underneath. This layer is responsible for the protection of the half-mask. All the half-masks mentioned were made in the form of slip molded bowls with a distinctly outlined nose and chin part. These features are not present in the last group of half-masks, denoted in the chart by curves I and J. These half-masks are characterized by low initial airflow resistance and a great value of the clogging coefficient. Both half-masks are trapezoid-shaped and are made of filtering material of thick fibers that perform the function of both an initial and main filter.

In half-mask J, an additional layer made of a nonwoven of low surface density was used, covering the layer of thick fibers placed under it. This is an element that improves dust-depositing properties of half-masks. On the basis of the results obtained from the measurements of clogging, an image of the changes of airflow resistance during the measurement has been made. On the basis of an analysis of the testing material obtained from a series of investigations of filtering half-masks and filters, it has been found that there is a great diversity of the ability to clog among the different types of half-masks.

In conclusion, it is possible to shape the clogging properties of respirators by selecting and joining different types of materials. The results presented in Figure 3 show that for some half-masks the time of loading until the state of excessive airflow resistance is shorter than for others and that this time closely depends on the clogging coefficient. Bearing in mind that the clogging coefficient is a measure of the

filter's ability to accumulate dust without raising airflow resistance too much, we tried to find the relation between this parameter and the basic structural features of filtering material, that is, initial breathing resistance and surface density of the outer layer. Figure 5, which presents the results of this analysis, suggests the effect of both mentioned parameters on the clogging coefficient.

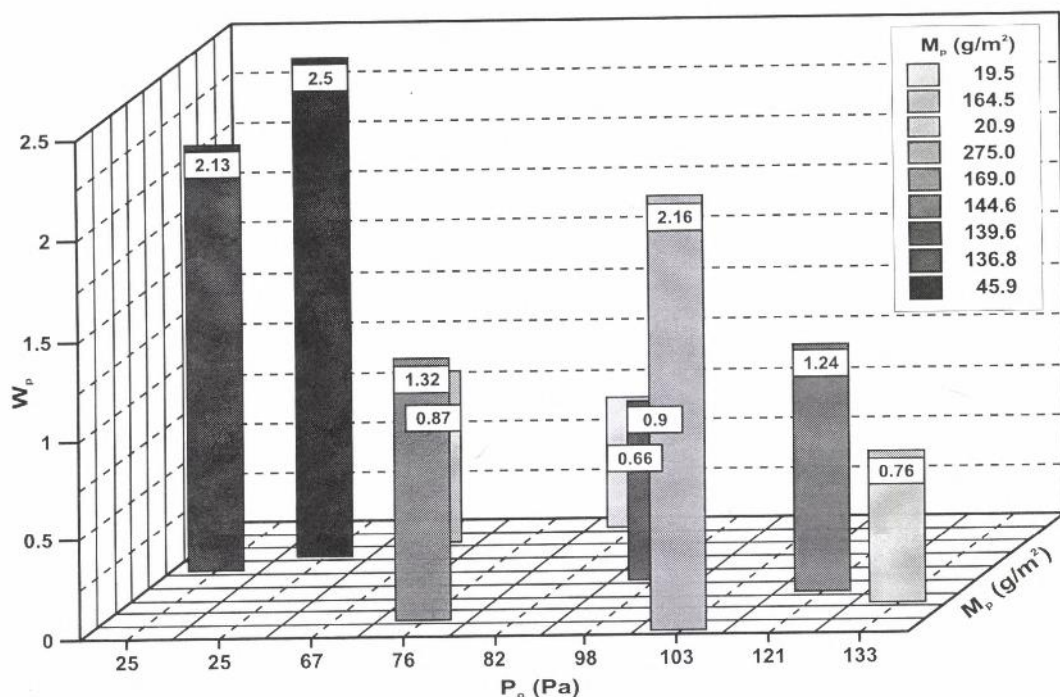


Figure 5. Relation between the clogging coefficient, initial airflow resistance, and the surface density of the outer layer (M_p) for tested half-masks.

The choice of respirators for different working conditions depends on those conditions and there are many situations in which respirators with low dust accumulation are useful. In such cases, it is advisable to use half-masks of low clogging coefficient, which are usually lighter and more comfortable. On the other hand, in high dust concentration, the respirator with higher dust accumulation over a longer period of time is necessary. One should choose from respirators of possibly low initial airflow resistance, which is understood as initial breathing resistance. Generally, the higher the surface density, particularly of the outer layer, the better the dust-cumulative properties.

Most of the manufactured respirators have layer systems composed of different filtering materials. During further investigations, four variants of different systems of filtering materials were produced (see Table 1, items 1-4). By analyzing the results of investigations into the dust-holding capacity of filtering systems, it has been established that the arrangements of layers differentiates the dynamics of the increase in airflow resistance during the deposition of dust. The filtering system marked C is a three-layer system, like A and B, but it basically differs in its outer layer made in

the form of a nonwoven of a low mass per unit area but of a large total surface. With the outer layer thus constructed, in spite of a high initial inhalation resistance, this filter shows relatively good dust-depositing properties.

The four-layer filter marked X, where an additional layer is placed between the outer and filtering nonwoven, is the one whose dust-cumulative properties are considerably different from the others. Such an arrangement results in an improvement of the dust-holding capacity although the same proportions between the mass per unit area of the outer layer and the mass per unit area of the whole filter are maintained. The results presented in Table 3 reveal the coincidence of the effect of at least two factors. One of them is the number of layers, the other is the surface density of the material, particularly of the outer layer.

When taking systems of the same number of layers and the same surface density, the same clogging coefficient is obtained. The addition of one layer causing the increase of surface density, even though insignificant, is the cause of a distinctive increase of the clogging coefficient. It is worth noticing that the surface density of the outer layer did not change at all. On the other hand, removing two layers (variant C in Table 3) causes the diminishing of the clogging coefficient even if the surface density of the whole system is higher. In variant C, raising the surface density goes together with a severe increase of the initial airflow resistance. However, the clogging coefficient is still relatively high and this is probably a consequence of a more fluffy structure of the whole system. The graph presented in Figure 4 shows that the changes of airflow resistance during dusting are different for variants X, C, and A and B (there is not much difference between variants A and B).

To reveal the pattern of dust deposition in different layers, three other systems of filtering material were investigated (items 5-7 in Table 1). The results are presented in Tables 4 and 5. The systems of the material were selected in such a way that the clogging coefficient was maintained on relatively the same level (about 1.4-1.5). The systems differed in the number of layers (3 or 4) and in the surface density of the outer layer. It turned out that most of the dust was deposited in the outer layer and that the mass of the deposited dust was related to the surface density of this layer, which confirmed the earlier considerations. The distribution of the dust between other layers is different and on the basis of the obtained results it is difficult to conclude about the reason. However, it is evident that in variant III, the third layer—which is the main filtering layer—is better protected against the challenge of coarse and heavy particles than in other variants. In variants I and II, quite a large amount of dust accumulates in the main filtering layer, which might negatively affect the filtering properties of the whole system. The best system of the considered ones is composed of four layers with a relatively thick outer layer.

6. CONCLUSIONS

The properties of filtering materials and the number and arrangement of layers, affect the filtering system's dust-holding capacity in the presence of great dust concentration. In order to improve the dust-depositing properties, the outer layer should be made of a nonwoven of relatively high surface density, produced from

thick, loosely packed fibers, so that dust particles can form dendrites of longer chains, which has an effect on their better packing in the filter structure. The introduction of an additional separating layer between the outer layer and the main filter will slow down the processes of clogging manifesting itself in an increase of airflow resistance due to the deposition of dust.

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