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A Study of the Nonsteady-State Filtration Process in a Fibrous Material in Conditions of Real Dust Loading

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The study concerns ways to describe filtration efficiency and gas flow resistance while particles are deposited in fibrous respiratory protective filters under conditions characteristic for their use. The performance of fibrous filter materials of varied structure and electrostatic properties was studied, using polydisperse coarse-grained aerosols and submicron aerosols of sodium chloride. Evidence was found that changes in airflow resistance depended to a large extent on air humidity and the concentration of the aerosol. A relationship was also found between the electrostatic properties of filter media and their decreasing efficiency with time. A numerical model was developed to simulate the phenomenon of nonsteady-state filtration for 2 mechanisms of deposition, which permitted assessment of the filtration characteristics of filter media of any design and in any conditions.

air filtration fibrous filtering material particular deposition
clogging test filtration efficiency gas flow resistance
simulated use of respiratory protective equipment
model of nonsteady-state filtration

1. INTRODUCTION

As far as the protection of health and life in a working environment is concerned, the concept of there being an inter-relationship between work safety and ergonomics is conducive to research aimed at optimal

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engineering of the working conditions. Correctly selected means of individual protection based on a careful analysis of the hazards and contingencies associated with the character of the work are an important element of every work safety system. This concept requires extensive studies including an analysis of the phenomena liable to occur in use, the elimination of possible hazards, and requirements concerning the efficiency of protection, and its effects on the user.

Among the toxic compounds that are often present in working environments are aerosols. They enter the body through inhalation, and the hazard associated with aerosols is more dangerous as their negative effect slowly increases, depending on their chemical composition, and proportionally to the individual's susceptibility and the amount of effort required by his or her work.

Individual respiratory protections against aerosols are a common solution, especially in such industries as mining, wood-working, building, and agriculture, where systemic solutions would be too costly. Unequivocal interpretation of the phenomena occurring in respiratory protective filter materials and their selection in terms of their effective life are difficult because of the diversity of the dusts and the complexity of the processes in which they are emitted and present.

In the relevant world literature, research on the filtration of aerosols has been confined to the effect of certain individual parameters of the process only (Brown, 1993; Cai, 1992; Davies, 1973; Emi, 1990). As far as filter materials used for respiratory protection are concerned, the essential problem has been to isolate the group of factors that are characteristic for the real use of the filters as well as their inter-relations and the role they play in the changes in filtration characteristics with time.

Therefore, research was started with the aim of explaining the character of the various hazards associated with dusts, paying particular attention to the climatic factors. Then a stand was developed for the simulation of nonsteady-state filtration in respiratory protectors. It provided the possibility to investigate the combined effect of the most important factors and their influence on protective efficiency and breathing conditions.

2. ANALYSIS OF THE CONDITIONS OF USE OF FIBROUS RESPIRATORY PROTECTIVE FILTERS

The phenomena discussed here, which take place during the real use of fibrous respiratory protective filters, are associated with nonsteady-state filtration. They are manifested by changes in the essential parameters of the filtration process, that is, efficiency of deposition and aerosol flow resistance, and are a result of continuous accumulation of particles in the filter material (Brown & Wake, 1998; Podgórski, Rudziński, & Gradoń; 1996). The following factors have a significant influence on the filtration process:

- properties of the filter media,
- character of the hazards,
- character of the gas flow as a function of the breathing cycle of the user.

The construction of a filter medium for respiratory protective filtration is based on fibrous materials, which can separate a certain amount of dispersed aerosol from the passing stream of gas by the mechanism of deposition. The ratio of the trapped particles to the total particles, referred to as deposition efficiency, is a determinant of the protection class of the filter material and is one of the factors that decide how the filter material can be utilised in respiratory protective equipment. Another factor of importance is the resistance to gas flow, which increases as more and more particles of the aerosol are deposited. It was found (Krzyżanowski & Majchrzycka, 1997) that the parameters of nonsteady-state filtration strongly depend on the structure of the filter material.

Fibrous filters of low density, usually produced by the needling technique, are characterised by low deposition efficiency and low resistance to gas flow. They are fairly resistant to clogging in contrast to high-density filter materials of high efficiency, which are made by the melt-blowing technique. The latter filters can trap a much lower volume of aerosol particles, and the deposited layer of dust forms a compact structure, leading to a rapid increase of the gas flow resistance of the filter. This also means deterioration of the breathing conditions.

Layered fibrous filter media are a compromise between efficiency and comfort of use. Deposition in them is additionally increased by induced electrostatic attraction between the fibres of the medium, which have an electrostatic charge, and aerosol particles. The electrostatically charged materials, referred to as electret materials (Ciach, Czwarno, & Gradoń, 1995), have notably improved the efficiency of anti-aerosol respirators, but more and more often now the possibility is signalled that this improved capacity is perhaps lost as increasing amounts of particles are deposited (Brown, 1979; Chen & Willeke, 1993; Podgórski, et al., 1996; Zakrzewski, Majchrzycka, Brochocka, & Makowski, 1996). As far as nonsteady-state filtration is concerned, this phenomenon may be additionally affected by the presence in the respiratory protective equipment of condensing water vapour, which was not taken into account in earlier investigations.

Most investigations concerning the phenomenon of nonsteady-state filtration were based on the assumption of a continuous flow of aerosol through the filter material. However, in the use of respiratory protective equipment, the breathing cycle of the user has to be taken into account. Therefore, investigations had to be verified to make allowance for a sinusoidally variable flow corresponding to the user's inhale-exhale cycle.

Taking as a basis worldwide theoretical and experimental research on nonsteady-state filtration and parameters that characterise the real use of respiratory protective equipment, a test stand was developed that could simulate the real use of the equipment under variable dust hazard conditions and that would provide an instrument for complex tests.

3. TEST STAND FOR TESTING NONSTEADY-STATE FILTRATION OF FIBROUS FILTERS AND TEST METHODS

Tests of nonsteady-state filtration were performed in a dust chamber as presented in Figure 1. The main part of the chamber was a transparent cylindrical container in which the flow of aerosol and deposition of dust particles could be observed throughout the loading process. The test sample of the fibrous filter material (F) was fixed in the sample holder located in the upper part of the dust chamber, at a distance of 200 mm from the aerosol inlet. Behind the sample an absolute filter (FA) was located. Its function was to collect the dust particles that passed through the test sample. Aerosol was generated by a disk feeder and a 100-mm long taper nozzle (A), which was connected with the air suction system. Dust concentration in the test medium was adjusted by varying the rotary speed of the disk and the volume of the air fed to the nozzle. The flow of aerosol through the sample in correspondence with the inhale-exhale phase was effected through inclusion in the test system of a two-cylinder artificial lung. Airflow resistance was measured by means of an electronic pressure gauge (M). The dust chamber was equipped with an ultrasonic humidifier and a thermo/hygrometer.

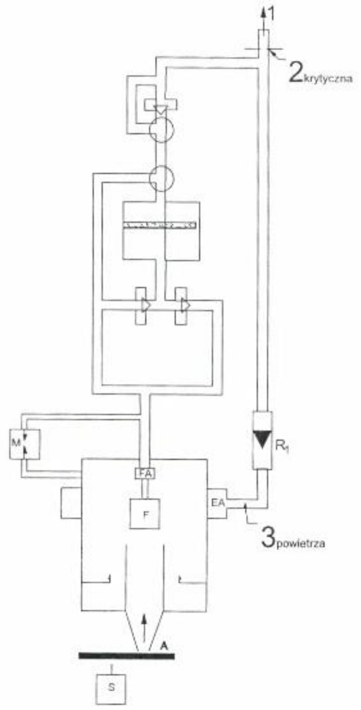

Figure 1. Test stand for testing fibrous filter materials in simulation of the real use of respiratory protective equipment. *Notes.* 1—air intake, 2—critical orifice, 3—air overflow.

The disk-type aerosol generator was not suitable for testing the filtration of submicron particles. Observation of the phenomena associated with the nonsteady-state filtration of this type of aerosols was made possible by using a device for measuring the penetration of sodium chloride particles of 0.6 μm. The procedure consisted in passing the aerosol through a hydrogen flame so as to agitate the atoms of sodium by means of high temperature. Then, the light of sodium-specific wavelength was optically filtered and the intensity of the emitted light was measured by means of a photo-multiplier. A diagram of the installation for tests based on a sodium-chloride aerosol is presented in Figure 2.

Tests were performed for fibrous filter materials produced by the needling technique from fibres with varied affinity to water, electret filter materials charged by the corona discharge method, and materials with triboelectric properties. The dusts used for testing in the dust chamber included silica dust of a mean particle diameter of 2.5 μm,

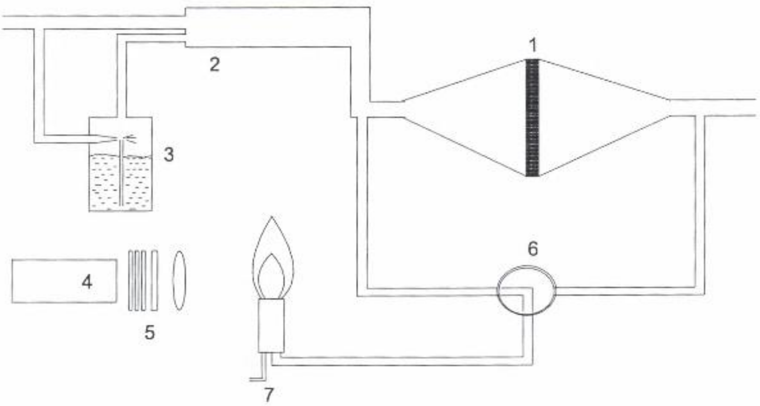

Figure 2. A diagram of the installation for testing fibrous filters with the use of NaCl aerosol. *Notes.* 1—tested filter, 2—dehumidifier, 3—aerosol generator, 4—sensor, 5—optical filters, 6—sample valve, 7—hydrogen.

dolomite dust (35 μm), and carbon dust (25 μm). The filter samples and the dusts were acclimatised under normal climate conditions. Dust concentration in the tests varied (100, 200, 300, and 400 mg/m^3) as did relative humidity (40, 60, 80, and 100%). Tests were performed for a continuous and an alternating airflow whose volumetric intensity was selected so as to correspond to medium-hard working conditions (48 dm^3/min). Evaluation of the nonsteady-state filtration process was based on recorded changes in filtration efficiency, airflow resistance, and weight of the dust entrapped in the filter medium on completion of the test.

4. TEST RESULTS AND THEIR ANALYSIS

The deposition of aerosol particles in the filter media is the normal consequence of using a respiratory protective filter in accordance with its purpose. While an aerosol is flowing through the filter, its particles are deposited on the filter elements in the form of agglomerations referred to as dendrites (Gradoń & Payatakes, 1982; Payatakes & Gradoń, 1980; Pich, Emi, & Kanaoka, 1987). The chains of dendrites keep growing in a continuous process from the moment they are initiated. This growing process is responsible for dynamic structural changes in the filter media, depending on their initial porosity (Krzyżanowski & Majchrzycka, 1997). These changes lead to significantly increasing airflow resistance and to local variations of the flow rate within the stream of the aerosol, causing variegation of the deposition efficiency. The question remains, though, to what degree such process factors as the type of the aerosol, dust concentration, relative humidity, the character of the airflow, or electrostatic properties of the filter can influence the process of nonsteady-state filtration for a given filter medium. The tests that could be carried out on the aforementioned stand for testing the behaviour of fibrous filter media in simulated use provided the possibility of analysing these changes. The most important relations associated with changes in airflow resistance are presented in Figure 3.

In filter media of similar geometry increasing airflow resistance is largely the effect of a combined action of aerosol particles, which are deposited in large amounts, and humidity in the form of water vapour

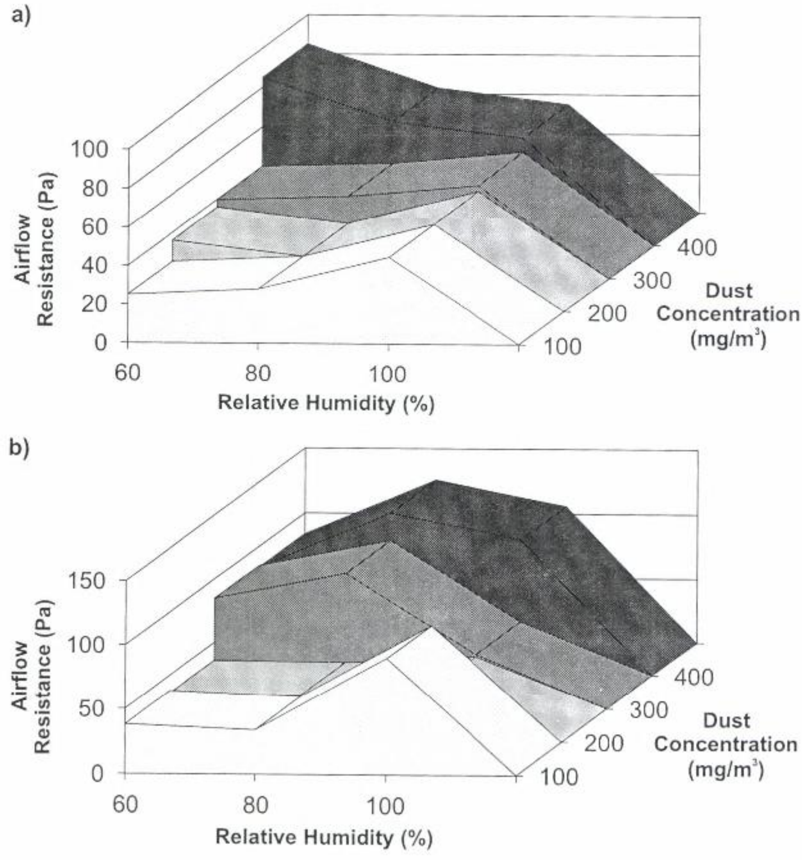

Figure 3. Dependence of airflow resistance variation on aerosol concentration and relative humidity (RH) for carbon dust deposition in (a) filters with electrostatic charge, (b) filters without electrostatic charge.

or condensing drops. Such conditions favour a compact structure of dust agglomerations that, by tightly adhering to the surface of the fibres, form new filter elements of greater diameters. As a result, increase in airflow resistance is much slower, which means that the behaviour of the same filter medium varies depending on the conditions of its use. In further analysis it was established that the character of the changes was independent of the type of the aerosol, the type of the filter material, or parameters of the flow.

For efficiency of deposition, of essential importance is the type of the filter material and the method by which it is imparted its electrostatic charge. In the case of non-charged filter materials, the deposition of aerosol particles is a factor that improves, with time, their efficiency. The explanation is that deposited particles reduce porosity of the fibro-granular structure, causing deposition of much finer particles that form a new filter layer of much higher efficiency. The humidity of the air or the hygroscopic properties of the filter material or aerosol particles do not affect the process very much. A reverse phenomenon was observed in the case of the electret filters. Test results for the filtration efficiency of electret filters, expressed as test-aerosol penetration, are presented in Figures 4 and 5.

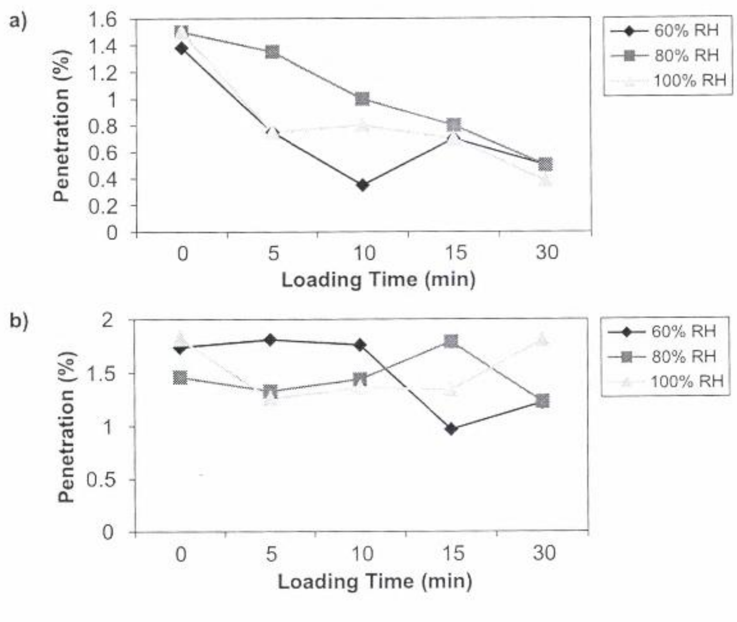

Figure 4. Relationship between changes in filtration efficiency and relative humidity (RH) for a filter material activated by corona discharge at (a) dust concentration of 400 mg/m^3, (b) dust concentration of 100 mg/m^3.

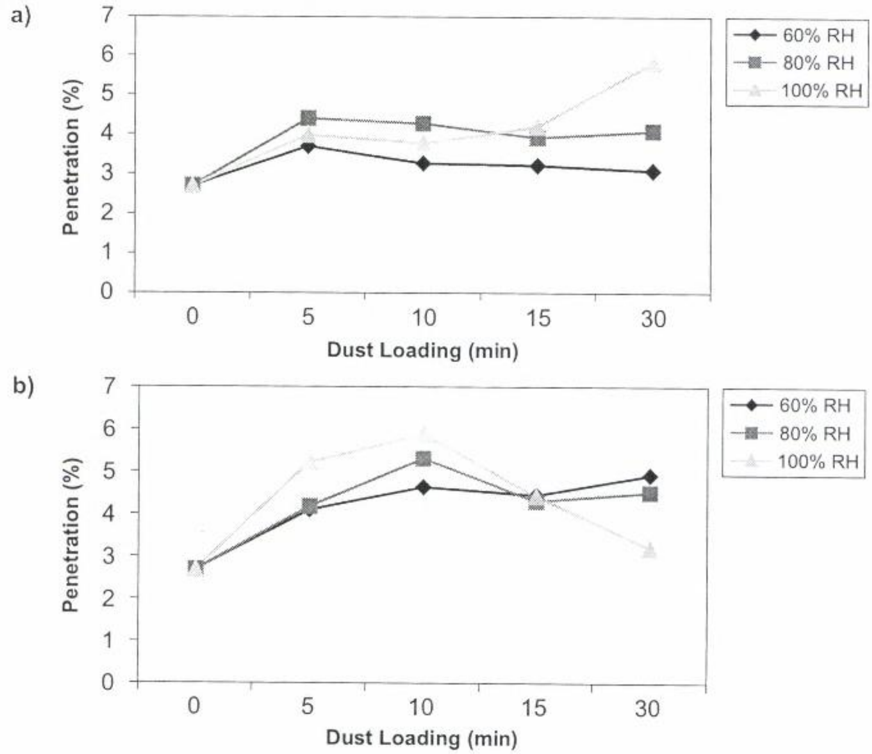

Figure 5. Relationship between changes in filtration efficiency and relative humidity (RH) for a filter material with triboelectric properties at (a) dust concentration of 400 mg/m³, (b) dust concentration of 100 mg/m³.

The depositing aerosol particles have a deteriorating effect on filtration efficiency, the deterioration being the greater the higher the relative humidity, the lower the aerosol concentration, and the weaker the electrostatic charge.

Our observations suggest that a filter material may lose its filtration efficiency while used despite its good protective properties in the initial phase of nonsteady-state filtration. Therefore, tests have been carried out to show that in the case of the electret filter materials used for respiratory protection, it is not sufficient to determine initial filtration efficiency. It is, therefore, necessary to determine not only initial efficiency but also the way this parameter changes throughout the process of nonsteady-state filtration. The tests were based on the use of the sodium chloride aerosol, which because of its particle size, is described as the worst-case aerosol. The results are presented in Figure 6.

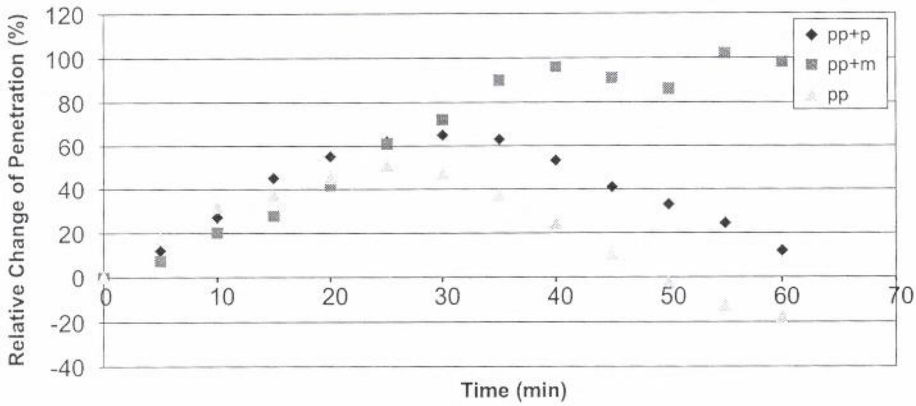

Figure 6. Curves of filtration efficiency variation expressed in terms of NaCl aerosol penetration for filter materials. *Notes.* pp—single corona-charged filter medium of low porosity; pp + p—double corona-charged filter medium of higher porosity; pp + m—double triboelectrically charged filter medium of highest porosity.

Curves were obtained for all tested filter materials, which showed that in the initial period of nonsteady-state filtration, efficiency decreased until a certain minimum specific for a given material was reached. From that moment, it increased until clogging. It was shown that the rate of the changes depended on the type of the filter material, especially its structure and electrification. Materials with triboelectric properties and considerable porosity lose their filtration efficiency at a much lower rate. That is why they reach their minimum protective capability much later than corona-charged materials whose porosity is low.

The alternating flow of air, corresponding to the user's inhale-exhale phase, has a definite effect on the mass of aerosol particles deposited in the filter material. The test results for the continuous and alternating airflow, obtained under the same process conditions are presented in Figure 7. Under the conditions of real use, airflow in the breathing cycle is conducive to better utilisation of the filter medium and is a factor improving the efficiency of deposition.

Laboratory tests revealed the complex character of the processes of nonsteady-state filtration and significant dependence of filtration characteristics on the type and structural parameters of the filter media as well as dependence of deposition efficiency variation and of airflow resistance on the conditions of use of the media. They pointed to the need to develop a model of simulated nonsteady-state filtration, which would help to optimise the construction of filter media in terms of their effective utilisation in respiratory protective equipment.

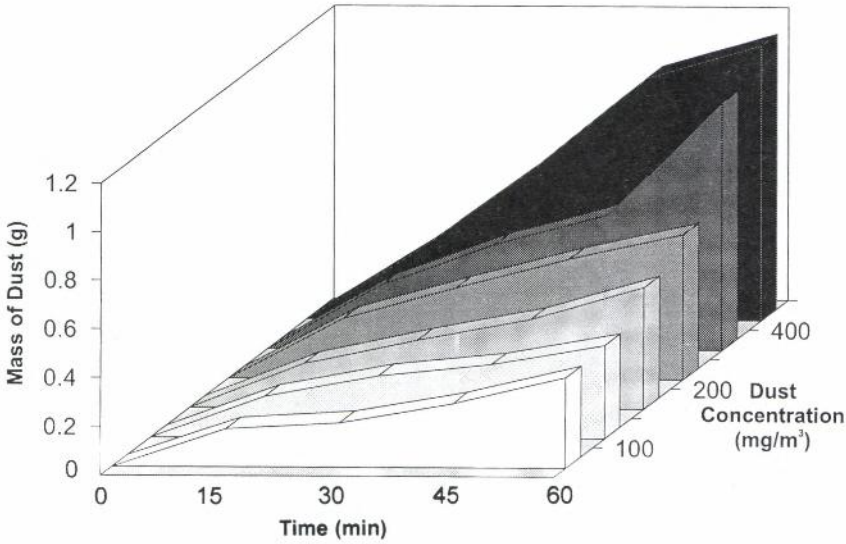

Figure 7. Mass of deposited dust as a function of aerosol concentration and character of the flow.

5. MODEL OF NONSTEADY-STATE FILTRATION

The generally adopted approach to modelling the aerosol deposition process consists in first analysing the properties of an individual fibre and then approximating the properties of the entire layer. To make an accurate calculation of the filtering performance of an individual fibre under real conditions, one needs to know the field gas flow around the fibre. In this study, recourse was made to the simplified solution provided by the Kubawara cell model (Brown, 1993). Using this model, solutions were found of equations describing the motion of a particle around one fibre within a cell whose boundaries are defined by nullification of the shearing stresses in the gas. In the model it was assumed that aerosol particles would be deposited by two mechanisms, depending on the size of the particles. For submicron aerosols, it was assumed that of essential importance would be the mechanism of diffusion, and for particles in the order of 2–5 μm flowing at a rate of 0.1 m/s the mechanism of direct interception (Emi, 1990) would be appropriate.

To calculate the de-dusting effect of each of the postulated two mechanisms of deposition, the following procedure was adopted with the assumption that each mechanism operates independently.

$$E_{12} = E_1 + E_2 - E_1 \times E_2 \quad (1)$$

where

E_{12} — deposition efficiency at joint operation of diffusion and direct interception mechanisms,

E_1 — deposition efficiency at operation of direct interception mechanism,

E_2 — deposition efficiency at operation of diffusion mechanism.

From the known efficiency of an individual fibre, efficiency of a single filtering layer of a thickness equal to the diameter of the fibre was calculated:

$$\eta = 1 - \exp\left(-\frac{4 \times E_s \times c \times l}{\pi \times (1 - c) \times d_f}\right) \quad (2)$$

where

η — efficiency of a single filtering layer,

E_s — efficiency of an individual fibre,

c — density of the layer,

l — thickness of the filtering layer,

d_f — diameter of the fibre.

The relation was derived with the assumption that the fibres in the layer are disposed parallel to one another and perpendicular to the gas stream. This relation (Equation 2) was used in the program that simulated the loading of filter layers.

The effect of the increasing mass of dust on changes in the filtration efficiency of an individual fibre was proposed on the basis of an experimentally derived linear relation in the following form:

$$E = E_0 \times (1 + m \times \lambda) \quad (3)$$

where

E — filter efficiency,

E_0 — initial efficiency of an individual fibre,

m — dust loaded,

λ — coefficient dependent on aerosol particle diameter.

For small particle diameters (<1 μm), coefficient λ takes values of about 3.5, whereas for large diameters (>5 μm) of about 4.

The effect of the accumulation of the aerosol in the filter medium on changes in flow resistance was taken account of, using the following semi-empirical relation:

$$\frac{\Delta P}{\Delta x} = \frac{V \times \mu}{\chi} \tag{4}$$

where

ΔP — pressure drop,
Δx — depth from filter inlet,
V — dimensionless accumulated particle volume,
μ — viscosity of the gas.
χ is expressed by the relation

$$\chi = \frac{d_f^2}{64 \times (1-\alpha)^{\frac{3}{2}} \times [1 + 56 \times (1-\alpha)^3]} \tag{5}$$

where

d_f — diameter of the fibre,
α — fiber packing density of filter.

The proposed model of deep filtration was used for designing the geometry of filter media and evaluation of their effective operating time under pre-set conditions of use. With the obtained data, it was shown that high efficiency of filtration, effective utilisation of the filter medium volume, and relatively low flow resistance could be obtained by designing a multi-layered system with constant porosity in each layer, and with the diameter of the fibres diminishing in the direction of aerosol flow. A similar conclusion was also suggested by laboratory tests.

6. SUMMING UP

The results of the analysis of the performance of fibrous respiratory protective filters when used under simulated real conditions show that the manner in which aerosols are deposited largely depends on the combined action of process factors such as dust concentration, humidity, and the character of the flow. As regards electret filters, if the history of the nonsteady-state filtration process is unknown, it may happen that respiratory protection with positive results of laboratory tests will lose its protective properties in the course of use. It has been shown that a new method is needed to test the efficiency of respiratory protective equipment, as the method used so far permits no more than an assessment of the initial penetration when the filter medium is still clean. When selecting respiratory protective equipment to protect against variable dust hazards, consideration should be given to the geometry of the filter layers, as it may provide data for an approximate assessment of how long the filter medium will operate under given dust hazard conditions.

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