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Influence of Structural Characteristics on Liquid Aerosol Filtration in Multilayer Nonwoven Fabrics of the Spunlace Type

Abstract
Multilayer nonwoven fabrics are an important part of fibrous filters used in ventilation systems. The run of the filtration process depends on the structure of the fabric system, the aerosol particle deposition mechanisms and the aerosol flow conditions. This article discusses, in terms of theoretical models, the results of investigation of flow resistance and the efficiency at the initial stage of aerosol filtration – in which the dispersed phase consisted of liquid particles – through multilayer nonwoven fabric systems with different structural parameters. Research results indicate the functional dependence of filtering properties on the structural parameters of the fibres studied (primarily the thickness and porosity) and aerosol flow parameters, such as the liquid aerosol flow rate. Results of research on multilayer systems of "spunlace" type nonwoven fabrics with particular focus on the analysis of pore fraction distribution may be of crucial importance in forecasting the use of multilayer nonwoven fabrics as filtering media for a given process of liquid aerosol filtration, considering the maintenance of the most advantageous filtration conditions.

Key words: *aerosol filtration, nonwoven fabrics, liquid aerosols, particle size distribution.*

Introduction

Multilayer nonwoven fabrics are a significant item among the filtering media applied to air filters in ventilation and air conditioning systems [1], both on a national scale and worldwide.

The process of the filtration of aerosol particles in multilayer nonwoven fabrics is still being studied due to the huge number of parameters affecting the efficiency of filtration in correlation with flow resistance, the impact of which is still not entirely known.

Analysis of the process of filtration in terms of changes in air flow resistance and efficiency of filtration is a complex issue, as these parameters are explicit functions of the structural parameters of nonwoven fabric, i.e. the diameter of fibres, the density of fibre packing (or nonwoven fabric porosity), fabric thickness, and conditions of air flow through the filtering medium.

The run of the filtration process depends on the structure of the fabric system, the aerosol particle deposition mechanisms and the aerosol flow conditions.

This article discusses, in terms of theoretical models, the results of investigation of flow resistance and the efficiency at the initial stage of aerosol filtration – in which the dispersed phase consisted of liquid particles – through multilayer nonwoven fabric systems with different structural parameters.

The process of the filtration of aerosols in nonwoven fabric composite systems was investigated in terms of changes in the air flow rate corresponding to the intermediate flow area. It is an area which is interesting, from a practical point of view, with respect to filtering media in ventilation and air conditioning systems. In scientific literature the majority of considerations on the aerosol filtration process are based on the assumption of the laminar flow of aerosols through layers of filtering media. Ptak [2] carried out theoretical and experimental work on seeking a model of the filtration of aerosols with a solid phase dispersed in the area of intermediate flow through nonwoven fabric beds made of synthetic fibre.

The current methods of making a bed of spunlace type fabrics result in the creation, during the process, of voids between the fibres in the form of channels of barely definable geometrical shape. With the growing thickness of the fabric, e.g. as a result of adding consecutive fabric layers one upon another, the laminar flow of aerosol through the system may change its nature to an intermediate one and in extreme cases even to a turbulent one.

Classical theory of aerosol particle filtration

The movement of aerosol particles in filtering media may take place as a result of diffusional deposition, inertial impaction, interception, gravity, or electric forces. They have been discussed in detail in professional literature [3 - 6].

Aerosol particles are usually retained as a result of the simultaneous action of a number of mechanisms. Each of them has a defined role which depends on numerous parameters, hence theoretical filtration models are very complex, and the effects of their application are not always consistent with practice and expectations.

In theoretical filtration analysis of the process of capturing particles from a flowing stream of aerosol in a filtering medium, models of isolated fibres are most often used, in which the medium is treated as a homogeneous system built of single, spaced fibres placed perpendicular to the direction of flow of the aerosol stream [4]. The degree of aerosol particles captured in the filtering media is characterised by the efficiency of a single fibre, which depends on the aerosol flow conditions and the capturing mechanism. The Reynolds and Knudsen numbers are non-dimensional parameters, defining the aerosol flow. Aerosol particle capture is defined by non-dimensional parameters which depend on the type of mechanism, i.e.:

- Peclet number for deposition by diffusional deposition,
- Stokes number for inertial impaction,
- interception parameter,
- parameter for capture of particles by gravity,
- parameter defining capture of aerosol caused by external force.

Figure 1 presents a graph of relationships between the efficiency of filtering

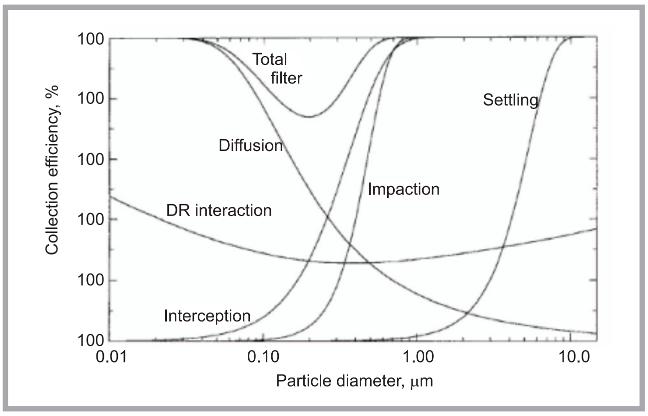

Figure 1. *Effect of particle diameter on the single fibre efficiency for different mechanisms of deposition. [3, 5].*

and the diameter of aerosol particles captured in the filtering media.

The efficiency of deposition of aerosol particles for specific mechanisms is used to define the total efficiency of a single fibre (E), which is then used to calculate the efficiency of the whole nonwoven fabric filter (η), according to the following relationship [3]:

$$\eta = 1 - \exp(-\lambda \cdot L) \qquad (1)$$

where:

$\lambda = \dfrac{4 \cdot E \cdot \alpha}{\pi \cdot d_{wl} \cdot (1-\alpha)}$ – coefficient of filtration,
L – thickness of nonwoven fabric,
E – total efficiency of a single fibre,
α – fibre packing density,
d_{wl} – average diameter of fibres.

In this research we analysed the efficiency values for aerosol particle deposition where the particle size was in the interval of 40 to 295 nm. In the case of small aerosol particles, as a consequence of collision with gas particles, they absorb energy which noticeably changes the direction of their movement [4]. The stochastic movement of particles is called Brownian motion. The diffusion mechanism is more significant for particles with diameters below 0.1 μm.

The diffusion mechanism's effectiveness with respect to particle capture is characterised by a parameter called the Peclet (Pe) number, calculated in accordance with the following formula [4]:

$$P_e = \frac{U \cdot d_{wl}}{D} \qquad (2)$$

where:
U – linear velocity of aerosol,
D – coefficient of diffusion,
d_{wl} – average diameter of fibres.

The diffusion coefficient (D) may be determined as follows:

$$D = \frac{k_B \cdot T \cdot C_n}{3 \cdot \pi \cdot \mu \cdot d_{cz}} \qquad (3)$$

where:
k_B – Boltzmann's constant,
μ – coefficient of viscosity,
T – absolute temperature,
d_{cz} – diameter of aerosol particles,
C_n – Cunningham correction factor.

The efficiency of deposition of particles on a single fibre as a result of diffusion (E_D) may be calculated from successive approximations of the following relationship [4]:

$$E_D = 2.9 \cdot K_u^{-\frac{1}{3}} \cdot P_e^{-\frac{2}{3}} \qquad (4)$$

where:
Ku – Kuwabara constant:

$$K_u = -0.5 \cdot \ln(\alpha) - 0.75 + \alpha - 0.25 \cdot \alpha^2 \quad (5)$$

The nature of aerosol particle flow against elements (fibres) of the filtering layer is featured by the Reynolds (Re) number, expressed as [4]:

$$R_e = \frac{U \cdot d_z \cdot \gamma}{\mu \cdot g} \qquad (6)$$

where:
U – linear velocity of aerosol,
d_z – effective size of fibre,
γ – specific weight of air,
μ – coefficient of viscosity,
g – standard gravity.

Based on experiments with loose materials, it was found that for $Re < 10$ the flow is laminar, whereas for $Re > 100$ it is turbulent [7]. Within the $10 < Re < 100$ range the flow is of a transitional nature between laminar and turbulent.

In accordance with the Darcy rule [4], the resistance of aerosol flow through filtering materials is a linear function of the aerosol flow rate, dynamic viscosity of the air and the thickness of the filtering layer. In the area of turbulent flow, this function may be expressed as follows:

$$\Delta p = \frac{\rho \cdot U^2 \cdot L}{2 \cdot d_{wl}^2} \cdot f(\alpha) \qquad (7)$$

where:
U – linear velocity of aerosol,
μ – coefficient of viscosity,
ρ – density of air,
L – thickness of nonwoven fabric,
α – packing density,
$f(\alpha)$ – dimensionless function relating pressure drop to parking fraction:

$$f(\alpha) = 16\alpha^{\frac{3}{2}} \cdot (1 + 56\alpha^3) \qquad (8)$$

d_{wl} – average diameter of fibres.

Test materials

The material selected for tests was in the form of nonwoven fabrics (designated as G, H & I) made from 100% polyester fibres using the spunlace technique. Spunlace type nonwoven fabrics are characterised by a structure which differs from those manufactured with the use of other textile techniques, including stitching with interweaving needles. The effect of combining fibres into a permanent product is achieved as a result of treating the fleece with water jets. Water jets with defined geometric dimensions are forced from nozzles at a preset pressure. They cause the strong entanglement of fibres as well as increase the friction between fibres and the density of the material to the desired value, thus giving a fabric the physical and chemical features required.

A structural characteristic of these nonwoven fabrics is given in ***Table 1***.

Three types of polyester fibres of different mean diameter were used in the nonwoven fabrics tested. The dimensions of fibres, in particular the fibre diameter, influence the porosity of nonwoven fabrics. The porosity of spunlace fabrics influences the filtering properties of multilayer sets, such as the pressure drop and filtration efficiency. Variations in the mean diameter of fibres made it possible to change the structure of the nonwoven fabrics, for example by obtaining different values of the main pore diameter.

The investigation consisted in determining the filtering properties of multilayer sets of nonwoven fabrics. The sets were composed of selected structural parameters (***Table 1***).

A diagram of the nonwoven fabrics tested (G, H & I) is shown in ***Figure 2***.

The thickness of the filtration structure was the variable in the multilayer nonwoven fabrics. The filtration structures tested were produced by layering single coats of nonwoven spunlace fabrics, which had constant values of surface mass, packing density, porosity and fibre diameter (***Figure 3***).

Microscopic analysis of the filtration process in the test nonwoven fabrics confirmed that liquid droplets wet the fibres, enabling surface tension to aid adhesion i.e. the phenomenon of the incidence of the deposition of droplets in places where fibres cross and between fibres.

Methods

Within the framework of tasks executed in the Filtration and Ventilation Laboratory of the Chemical and Dust Hazards Department at the Central Institute for Labour Protection – National Research Institute [8, 9], we constructed and launched a test post which allows measurement of the flow resistance and efficiency of the filtration of aerosol particles in filtering media of different structures and in various air flow conditions.

The test post was equipped with two measuring modules. The first module comprised a system for the preparation of nonwoven fabric samples to investigate the filtering properties and equipment required to define the structural parameters of the multilayer nonwoven fabrics.

The preparation stage of the samples for tests and determination of their structural parameters was carried out in accordance with the provisions of Standards ISO 9073-2:1995 [10] and ISO 139:2005 [11].

The nonwoven fabric composite systems of fabrics G, H, I were composed of fabrics of the same morphology. In cases of selected composites, structural parameters were determined, including the thickness (in accordance with a method described in detail in Standard ISO 9073-2:1995 [10]), surface mass (in accordance with Standard EN 29073-1:1992 [12]), porosity (with the use of Capillary Flow Porometry 4.900 (Porous Materials Inc., USA)), fibre diameter (with the use of microscopic image processing and the analysis system MultiScanBase v. 8.08 (CSS Ltd., Warsaw) and packing density (with the use of an analytical method).

Table 1. *Structural characteristic of the spunlace nonwovens manufactured from polyester fibres.*

Type of nonwoven fabrics	Thickness L_{av}, m	Surface mass M_p, g/m^2	Packing density α_{av}, kg/m^3	Total porosity ε_{av}, %	Average fibre diameter d_{av}, μm	Main pore diameter D_p, μm
G	0.00432	303.75	70.41	94.75	54.77	160.47
H	0.00644	295.18	46.72	96.51	18.06	48.59
I	0.00208	534.33	257.83	80.76	16.52	34.95

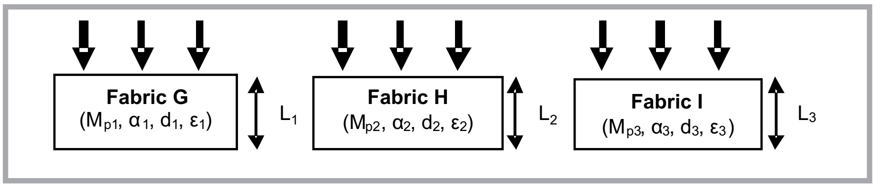

Figure 2. *Schematic of the single layer nonwoven fabrics tested.*

Procedures were developed for the investigation of changes in filtration parameters characteristic of multilayer nonwoven fabrics, such as the air flow resistance and efficiency of filtration, depending on the different structural parameters of the filtering nonwoven fabrics.

Changes in the flow resistance and efficiency of the filtration of aerosol particles were determined in the second measurement module with the use of a digital differential micro manometer and particle count methods. A schematic diagram of the experimental setup is shown in ***Figure 4***. The experiments were carried out using a setup composed of the following elements:

- aerosol generator AGF 2.0 iP (Palas GmbH, Germany) (3) with air filter (1) and internal pump (2),
- differential mobility analyser, DMA Model 3080L (TSI Inc., USA) (10),
- condensation particle counter, CPC Model 3022A (TSI Inc., USA) (11),
- PC computer (12),
- digital differential micro-manometer (8),
- sampling tubes for particle counter (5, 6),
- air velocity, temperature and relative humidity measuring system VIVO (Dantec Dynamics, Denmark) (9),
- flowmeters (13),
- constant volume pump (14),
- filter holder (7),
- throttling valves (4).

The flow resistance in a sample of composite systems of nonwoven fabrics with known structural parameters were measured prior to releasing aerosol into the system. The resistance was measured with the use of a digital differential micro manometer (IMG PAN, Kraków).

The efficiency of filtration through the multilayer nonwoven fabrics was tested with the use of aerosol of the sebacic acid-bis (2-ethylhexyl) ester (DEHS) type. The efficiency of filtration as a function of particle sizes for a given sample of the nonwoven fabric composite systems was determined based on the quantitative concentration of particles of the test aerosol upstream and downstream of the sample studied. The system used consisted of a SMPS 3936 scanning mobility particle sizer (TSI Inc., USA) containing a DMA 3080L differential mobility analyser and CPC 3022A condensation particle counter.

The aerosol sample first passes through a single-stage, inertial impactor. This serves to remove large particles outside the measurement range that may contribute to data inversion errors caused by multiple charging. Next, the aerosol passes through a bipolar ion neutraliser. This creates a high level of positive and negative ions and brings the aerosol charge level to a Fuchs' equilibrium charge distribution. The charged and

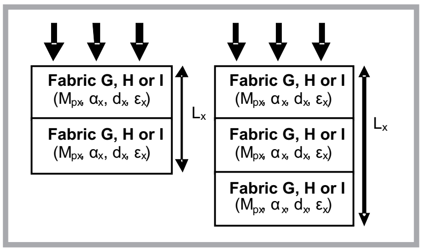

Figure 3. *Schematic of multilayer nonwoven fabrics tested.*

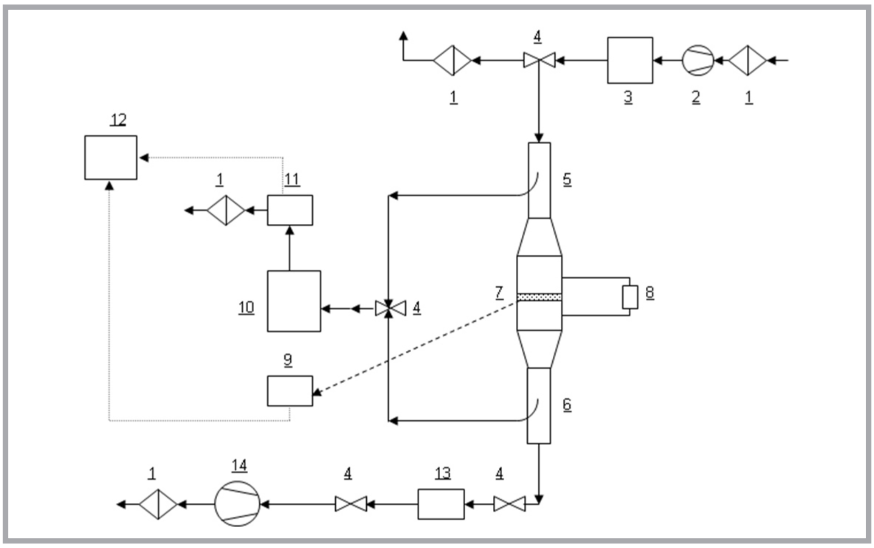

Figure 4. Schematic of the instrumental setup; 1) air filter, 2) internal pump, 3) aerosol generator, 4) throttling valves, 5, 6) sampling tubes for particle counter, 7) filter holder, 8) digital differential micro-manometer, 9) air velocity, temperature and relative humidity measuring system, 10) differental mobility analyser, 11) condensation particle counter, 12) PC computer.

neutral aerosol particles then enter the DMA 3080L in which particles are separated according to their electrical mobility. The DMA 3080L is constructed of two concentric cylinders: an inner electrode, and an outer electrode. The outer electrode is kept at ground potential, while a precise, negative voltage is applied to the inner electrode to create an electric field. HEPA-filtered, flow-controlled, laminar sheath air flows along the annual space between the two electrodes. Aerosol particles are introduced into the DMA 3080L through a slit at the top of the outer electrode. Particles with negative charges are repelled towards and deposited on the outer wall. Neutral particles exit the DMA 3080L with the excess air. Particles with positive charges move rapidly across the clean sheathair layer towards the negatively charged inner electrode. Only particles within a narrow range of electrical mobility have the correct trajectory to pass through the narrow, open slit near the bottom of the inner electrode. After exiting the DMA 3080L, the particles classified are counted by the CPC 3022A, which accurately measures the particle concentration. By ramping the voltage of the inner electrode exponentially over a user-selected period of time, the entire particle size distribution and number concentration are measured to a high degree of accuracy.

Investigation of the flow resistance and efficiency of the filtration of DEHS aerosol particles within the 40 to 295 nm diameter range in nonwoven fabrics was carried out in respect of four flow rates within the scope of 1.00 to 1.75 m/s through the multilayer nonwoven fabrics. In the preset range of linear velocity rates and for the test multilayer nonwoven fabrics with defined structural parameters, the flow was of a transitional nature and fell within the range of values of the non-dimensional Reynolds number between 16.19 and 92.27.

A detailed description of methods for investigating changes in the filtering properties of multilayer nonwoven fabrics was presented in earlier publications [13, 14].

Results of investigation of the change in resistance of aerosol flow through multilayer nonwoven fabrics

Table 1 presents structural parameters, including the thickness (L_{av}), total porosity (ε_{av}) and surface mass of the nonwoven fabrics (M_p), the size of the main pore diameter (D_p), fibre diameter (d_{av}) and packing density (α_{av}).

Figure 5 presents changes in flow resistance depending on the aerosol flow rate through spunlace type multilayer nonwoven fabrics.

Analysis of the graph in ***Figure 5*** shows that composite systems for nonwoven fabrics in the area of transitional flows disclosed a power function nature.

The curves of change in the resistance of aerosol flow through multilayer nonwoven fabrics made in the transitional flow area are more similar to theoretical curves defined in accordance with the Darcy equation used for calculation of the turbulent flow area.

Nonwoven fabric G has lower values of total porosity than fabric H. Nevertheless, as compared with fabric G, fabric H exhibits greater flow resistance with the increasing thickness of the multilayer system. Simultaneously, the size of pores in fabric H is more than three times smaller than that in fabric G. The thickness of fibres from which fabric H is made is several times the thickness of those of fabric G. This means that the number of fibres per volume unit of fabric H is several times greater than that of fabric G, with a similar mass of fibres in both these types of fabrics. During the flow, the stream of aerosol must wash a larger number of fibres in fabric H than in fabric G, hence the flow resistance must be greater. The greater flow resistance in fabric H also results from the smaller pore size. This explains why fabric H exhibits greater flow resistance and a higher rate of growth of flow resistance with the increasing thickness of the fabric system as compared with nonwoven fabric G. The mass of fibres per volume unit of fabric H is slightly smaller than that of fabric G; this is used as a basis for calculation of the total porosity of the fabric, which must exhibit a greater value for fabric H than for fabric G.

We can therefore draw a conclusion that analysis of the various relationships, describing the filtering properties of two or more nonwoven fabrics made of the same fibres but differing considerably in thickness, cannot be based solely on the total porosity. A comprehensive view of fibre porosity may be obtained through analysis of the total porosity value and distribution of the main fraction of pores in the Fabric I is characterised by high flow resistance and the very quick increment of this with the increasing thickness of the composite system. Among fabrics G, H and I, the latter is made of fibres with the smallest diameter - 16.52 μm. These three factors bring about the very quick increment of this resistance with the increasing thickness of the composite material.

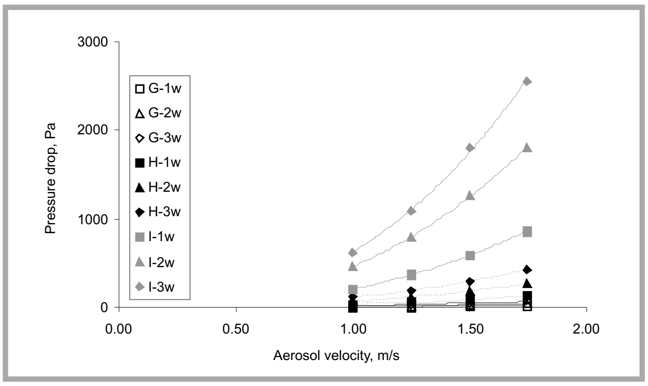

Figure 5. *Effect of the face velocity on the pressure drop in the transitional flow.*

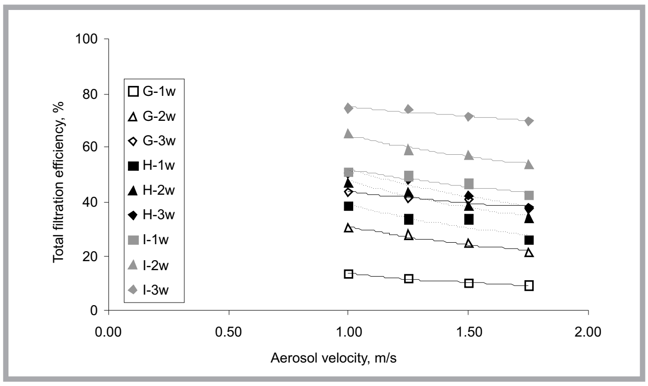

Figure 6. *Effect of the face velocity on the total filtration efficiency in the transitional flow.*

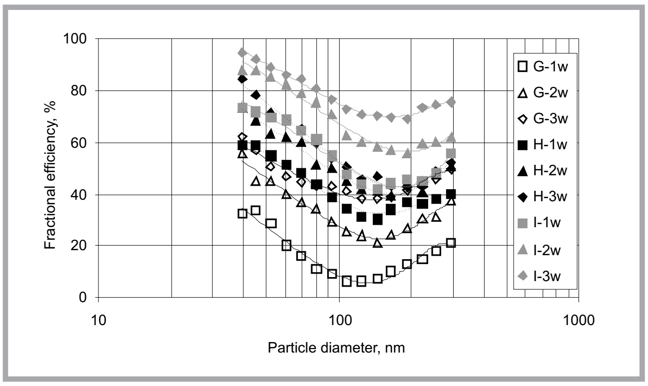

Figure 7. *Fractional efficiency of the multilayer systems at an aerosol velocity U = 1.00 m/s.*

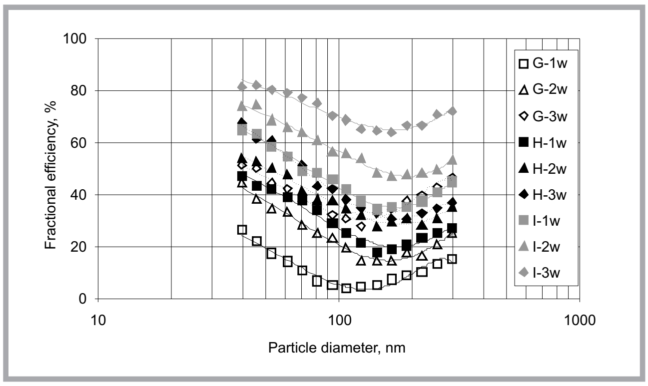

Figure 8. *Fractional efficiency of the multilayer systems at an aerosol velocity U = 1.75 m/s.*

Results of research on changes in the efficiency of aerosol filtration through multilayer nonwoven fabrics

Changes in filtration efficiency depending on the aerosol flow rate (transitional flow area) through the multilayer nonwoven fabrics are presented in ***Figure 6***.

Analysis of the graph in ***Figure 6*** shows that changes in the filtration efficiency of multilayer nonwoven fabrics defined in the area of transitional flows were of an exponential nature.

Exponential curves were of a negative nature, where their inclination vs the total efficiency of filtration axis grew with the increasing thickness of the multilayer nonwoven fabrics. This indicates the important role of the thickness of filtering layers when modelling their filtering properties.

The graphs presented show that the thicker the multilayer nonwoven fabric, the higher the efficiency of aerosol particle filtration is. We could simultaneously observe that experimental curves of the change in the filtration efficiency of DEHS liquid aerosol through the multilayer nonwoven fabrics occurring in the area of transitional flows are similar to the curves defined in accordance with the equation used in the classic theory of filtration [3]. This may prove that the studied multilayer systems of spunlace type nowoven fabrics with defined structural parameters may be of practical importance during the aerosol filtration process, where the dispersed fraction consists of liquid particles.

The results of investigating the fractional efficiency of multilayer systems of spunlace type nonwoven fabrics defined at two extreme flow rates U = 1.00 m/s and U = 1.75 m/s are presented in ***Figures 7*** and ***8***, respectively.

Data presented show that the nature of the curve of the change in filtration efficiency with a change in the diameter of aerosol particles is similar for all the types of multilayer systems of spunlace type nonwoven fabrics studied. Fractional efficiencies of multilayer nonwoven fabrics diminish in the area of aerosol particles 40 nm in size to the most penetrating particles (MPPS), whereas for particles larger than the MPPS type , the filtration efficiency grew. For all the multilayer nonwoven fabrics studied, we may observe different scopes of sizes of the most penetrating particles, for which the filtration efficiency reached the minimum. ***Table 2*** presents values of the minimum filtration efficiency related to the size of aerosol particles for the multilayer nonwoven fabrics.

During analysis of the changes in filtration efficiency in the function of the thickness of the multilayer nonwoven fabrics defined for two extreme aerosol flow rates, it was found that the greatest growth in filtration efficiency for MPPS particles occurred when there was an additional second filtering layer. A two-fold growth in the sample thickness caused a 3.4 fold growth in the minimum filtration efficiency in multilayer systems of fabric G and a growth of 1.3 to 1.6 times in the efficiency of the filtration of MPPS particles in multilayer systems of fabrics H and I. The addition of a further layer of fabric G caused comparable growth in filtration efficiency, i.e. between 2.8 and 3.2 times. However, a further increase

Table 2. *Minimum fractional efficiency of multilayer nonwoven fabrics at different aerosol velocities.*

Type of multilayer nonwoven fabric	MPPS particles, nm		The minimum filtration efficiency, %	
	Aerosol velocity U = 1.00 cm/s	Aerosol velocity U = 1.75 cm/s	Aerosol velocity U = 1.00 cm/s	Aerosol velocity U = 1.75cm/s
G-1w	124	107	6.19	4.25
G-2w	143	124	21.14	14.67
G-3w	143	124	38.17	28.20
H-1w	143	143	30.50	18.11
H-2w	165	143	39.25	28.03
H-3w	191	165	42.81	30.56
I-1w	143	143	42.18	34.22
I-2w	191	165	56.05	46.90
I-3w	191	165	69.11	63.82

in the thickness of multilayer systems of fabrics H and I did not cause as large increment in the total efficiency of filtration (***Table 2***).

Comparison of the minimum values of efficiency obtained in respect of MPPS particles shows that with a growing aerosol flow rate, the values of filtration efficiency decreased for specific particle sizes. With a growth of 75 per cent for the flow rate of DEHS aerosol, the falling minimum values of filtration efficiency correspond to equal or smaller values of MPPS particle diameters, i.e.:

for multilayer systems of nonwoven fabric G - between 124 nm and 143 nm (for U = 1.00 m/s) and between 107 nm and 124 nm (for U = 1.75 m/s),

for multilayer systems of nonwoven fabrics H and I - between 143 nm and 191 nm (for U = 1.00 m/s) and between 143 nm and 165 nm (for U = 1.75 m/s).

Conclusions

In accordance with the generally accepted filtration theory, the filtering properties of multilayer nonwoven fabrics produced with the use of the spunlace technique depend on their structural parameters and aerosol flow conditions. This is confirmed by the research results, which indicate the functional dependence of filtering properties on the structural parameters of the fibres studied (primarily the thickness and porosity) and aerosol flow parameters, such as the liquid aerosol flow rate.

Analysis of the curve of changes in the filtering properties of multilayer systems of spunlace type nonwoven fabrics shows that the construction of multilayer systems, with particular focus on two- and three-layer systems, is rational only in the case of nonwoven fabric with an apparently larger diameter of fibres and size of pores of the main fraction. In the case of nonwoven fabrics with lower fibre diameter values and size of pores of the main fraction, the growth in aerosol flow resistance with the increasing thickness of the multilayer systems is sufficiently quick to level the simultaneous growth in the total efficiency of aerosol particle filtration.

Changes in the flow resistance and efficiency of filtration are more essential with an increase in the aerosol flow rate through the fabric multilayer system.

Analysis of the results of the research shows that the curve of changes in the aerosol flow resistances through the multilayer systems of filtering nonwoven fabrics occurring within the area of transitional flows are similar to theoretical flows defined in accordance with the equations used for the area of turbulent flows.

It was found that the total porosity is not the sole index used in the analysis of relationships describing the filtering properties of two or more fabrics that are made of the same fibres but with a noticeably different thickness. A comprehensive view on the porosity of fabrics may be obtained through an analysis of the distribution of the main fraction of pores in the nonwoven fabric.

Results of research on the multilayer systems of spunlace type nonwoven fabrics with particular focus on analysing pore fraction distribution will be used as the basis for further work on the determination of experimental changes in filtering properties with respect to economic changes in structural parameters and their verification with existing theoretical descriptions of the process of the filtration of liquid aerosols in filtering layers.

This may be of crucial importance in forecasting the use of multilayer nonwoven fabrics as filtering media for a given process of liquid aerosol filtration, considering the maintenance of the most advantageous filtration conditions, i.e. the high efficiency of filtration and low resistance of aerosol flow.

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