Separation of Nanoparticles from Air Using Melt-Blown Filtering Media

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ABSTRACT

Over the last few years, expectations have grown for the development of appropriate materials for separation of nanoparticles of different morphologies from air. Therefore, the objective of this work was to conduct a broad study of the process of filtration of polydisperse nanoaerosols in materials of our design and production. They were made using the modified melt-blown technology, a very promising technique that allows to produce large amounts of fibers with a wide range of diameters which when properly formed in mats or cores can be used in various filtering products, such as protective masks, car filters. The filtration efficiency for KCl solid nanoparticles and DEHS (di-ethyl-hexyl-sebacat) liquid nanoparticles in three polypropylene filters of different morphologies have been established. The obtained results show how the aerosol face velocity and the morphology of the nonwoven media affect the filtration efficiency and pressure drop. It turned out that fibrous filters of our own production can separate particles with very small diameters from the air. As the effectiveness of the separation grew with a decrease in diameter of filter fibers, a filter composed of nanoscale fibers proved to be the most effective. An increase in aerosol flow velocity through the filter negatively affected its filtering effectiveness. The observation of data for cubical KCl and spherical DEHS particles, showed no differences in filtering effectiveness, which proves that for the tested diameter range the morphology of particles removed from air does not play a significant role, as it does for larger particles. The results obtained from the filtration of polydisperse nanoaerosols were successfully interpreted using our Partially Segregated Flow Model which takes into account the polydisperse distribution of fiber diameters in the filter. What is more, it shows that the application of the classical theory of filtration significantly overvalues the results obtained in our experiments.

Keywords: Nanoparticle measurement; Filtration; Fabric filters; Aerosol deposition; Aerosol generation.

INTRODUCTION

Over the past decade, the subject of nanometric particles has considerably grown in significance. Based on their origin, the particles can be divided into natural ones, that is those that can be found in the biosphere regardless of human activity and man-made, specifically designed particles (e.g., fullerenes, nanotubes) including those unintentionally produced in various technological processes. The size of many dangerous air pollutants (viruses, soot aggregates emitted by diesel engines, etc.) is of the order of nanometers, thus due to their size, they can easily penetrate through the human respiratory tract. Studies have shown that fine particles, defined as those less than 100 nm in diameter, have a greater impact on health (Donaldson et al., 1998; Granum and Lovik, 2002; Gorbunov et al., 2013), the environment (Dreher, 2004; Moore, 2006), and visibility (Kittelson, 1998) than larger ones. Hence, the purposefulness of such research is justified by, among others, the need to trap intentionally produced nanoparticles and protect people and the environment from detrimental particulates.

Along with the development of nanotechnology, the number of workers subjected to the so-called occupational exposure will also increase. It is therefore necessary to develop materials to effectively capture hazardous nanoparticles, either in the form of masks (Shaffer and Rengasamy, 2009; Mostofi et al., 2010) or protective clothing (Golanski et al., 2009; Pant et al., 2011). In this respect, there is a need to extend experimental and theoretical research aimed at more thorough understanding of the mechanisms of effective removal of nanoobjects from air. This process is however very hard to study because of the difficulties linked to the generation of high concentrations of well-defined nanoparticles and problems related to reliable measurements of such small objects. It is only through correct detection and exact description of nanoparticles that potential risks can be identified, controlled, eliminated or reduced. In the work by Sabbagh-Kupelwieser et al. (2011), a variety of characterization methods and measurable parameters concerning the wide range of particle diameters including...
nanoscale particles can be found. Chen and Chein (2006) described the method of generation and evaluation of monodisperse sodium chloride and oleic acid nanoparticles.

The separation of particles of different nanosizes from gas streams is as important as difficult to put into practice. Works already carried out in this area seek to discover the phenomena that govern the deposition and interactions of nanoparticles on collectors in order to design new materials or to improve those currently used to remove nanoparticles from gas streams. Nanosized particles are particularly difficult to remove using conventional devices, such as inertial precipitators, cyclone collectors, low-pressure impactors, etc. A number of studies of the nanoparticle filtration has been carried out for wire screens or tubes (Cheng et al., 1990; Shin et al., 2008; Yamada et al., 2011). Experimental data of penetration of nanoparticles in the 4–30 nm size range through fiberglass filters perforated with defined pinholes were presented by Mouret et al. (2009). Zarutskaya and Shapiro (2000) described the results of simulations compared to experimental data of nanoparticle penetration through magnetic filters. Liu et al. (2011) proposed covering a layer of fibrous filters with a membrane, which showed a greatly improved efficiency of the separation of airborne nanoparticles. Fibrous materials are popular, a very promising medium in a wide array of separation processes. They are used in air and water filters, disposable respirators, automotive cabin, hoover bags, and industrial gas cleaning devices (Barhate and Ramakrishna, 2007; Brochocka et al., 2013). The filtration of micron- and submicron-sized aerosol particles in such materials has been thoroughly explored (Zhong and Pan, 2007; Leung and Hung, 2008), however nanofiltration still remains only partially discovered. Experimental investigations into nanoparticle filtration through fibrous filters include works by Podgórski et al. (2006), Boskovic et al. (2008), Leung et al. (2009) and Pencone et al. (2015). There are not many mathematical models describing this phenomenon (Wang et al., 2007). One of them was proposed by Przekop and Gradoń (2008) who used the lattice-Boltzmann method to calculate the deposition efficiency of nanosized particles for the system consisting of two nano- and microsized fibers.

Within the framework of this paper, polymer fibrous filters were produced using a modified melt-blown technique developed by our research group, and then tested for their capability of separating nanoparticles of different morphologies from air. This study has some advantages over previously published research results, because the vast majority of them were conducted on commercially available, multipurpose filters, whereas on the basis of the experiments and mathematical model, own filter materials for specific applications can be produced.

A new test bench was developed and modified accordingly in cooperation with Palas GmbH Company to eventually get stable and reliable measurements of separation of nanoparticles from the air, which are most difficult to generate and detect. The influence of a number of very important factors on the course of the nanofiltration process was tested, including the size of aerosol particles, their morphology, the velocity of aerosol flow through the filter and the structure of the separating material. In addition, the obtained data were interpreted using the classical theory of filtration (Hinds, 1999), which states that the Brownian diffusion is the dominant mechanism for determining the filtration efficiency of nanoparticles, and the Partially Segregated Flow Model (Podgórski, 2009; Podgórski et al., 2011; Jackiewicz et al., 2013) proposed by our research group. Up to now, the model was examined whether it can be used to describe the process of separation of sub-micron and micron-sized solid particles and monodisperse nanoparticles. This model, unlike the classical theory of filtration developed for an idealized filter of a homogeneous structure made up of identical fibers evenly distributed over the entire filter material, takes into account the heterogeneous structure of fibrous filters and more specifically the polydisperse distribution of fiber diameters. Thus, this paper presents a comprehensive approach to the subject of nanofiltration from a manufacturing of melt-blown filters to checking their capability for effectively removing nanoparticles from air stream using technologically advanced equipment and to a theoretical description of the process.

MATERIALS AND METHODS

Melt-Blown Technology

The melt-blown technology is widely used in the manufacturing of fibrous filters on an industrial scale. The method developed in the US in the 1950s is now one of the fastest growing and most modern methods of manufacturing of polymer fibers. Compared to the alternative electrospinning method (Teo and Ramakrishna, 2006; Jaworek et al., 2009; Yun et al., 2010), the melt-blown technology allows to produce significantly larger quantities of fibers in a shorter time and at reduced cost. Due to the solid state of the polymer used in this process, the problem of toxic solvent fumes produced during electrospinning with polymer solutions can be also eliminated. The diameters of fibers drawn in the stream of hot air range from nanometers to micrometers, if appropriate parameters of the process are maintained, which results in a wide range of possible applications. Filter mats produced using this technique are characterized by polydisperse distribution of fiber diameters with an average diameter close to the set value. Raw materials used in this method were thermoplastic polymers with a high degree of polymerization, relatively low melt viscosity, and relatively small branching of their polymer chains. Those properties determine the so-called polymer spinnability, and their fulfillment guarantees high-capacity manufacture of high quality fibers.

All the materials used for research in the framework of this paper had been manufactured using the melt-blown technology on a modern equipment located at the Faculty of Chemical and Process Engineering of the Warsaw University of Technology (Fig. 1). In this modified method, polymer is melted and fed in the form of granules to a screw extruder and then expelled through a specially designed nozzle where it meets a stream of hot air. The construction of the nozzle and carefully selected process parameters (polymer and air flow rates, temperature in the heating
Fig. 1. The system for the production of filters using the melt-blown technique and a specially designed nozzle where fibers are formed.

| Filter  | Filter thickness $L$ [mm] | Filter solidity $\alpha$ [-] | Basis weight $q_s$ [g m$^{-2}$] | Arithmetic mean fiber diameter $d_F \pm \sigma_F$ [µm] |
|---------|--------------------------|-----------------------------|-------------------------------|---------------------------------|
| Filter F10 | 2.98                      | 0.105                    | 282.9                         | 9.62 ± 0.76                     |
| Filter F5  | 1.81                      | 0.072                    | 117.1                         | 5.60 ± 0.99                     |
| Filter F0.5 | 1.75                      | 0.029                    | 54.9                          | 0.47 ± 0.83                     |

Filtering Media

At the first stage of the research, the characteristic of the morphology of three different filters was established together with their structural parameters contained in Table 1. To produce filter materials polypropylene granules of very high chemical purity, identified as Metocene MF650 with Melt Flow Index 1800 were used. The low viscosity of the polymer (greater MFI) used to manufacture filters allows us to get the filaments with a wide range of diameters from nano- to microsized. The density of the material was 910 [kg m$^{-3}$].

In order to identify the structure of the new filtering materials, five samples from different parts of the filter mats were taken, weighed and measured for thickness, and the collected data averaged. The samples were weighed using electronic scales and the thickness of the filter was measured with a slide caliper with accuracy of 0.01 mm. Based on those parameters, the packing density of the fibers, $\alpha$, was established as the ratio of the mass of the sample, $m$, to the product of the surface area, $F$, thickness, $L$, and density of the material they were made of, $\rho$. The surface density of the filters, $q_s$, was also calculated as the ratio of the mass of the sample to its surface.

Next, using a series of images from Hitachi scanning electron microscopes TM-1000 and SU 8000 made for each fabric the fiber diameters distribution was defined with a geometric mean fiber diameter, $d_{Fg}$, and geometric standard deviation, $\sigma_{gdF}$, (Fig. 2). It was stated that the obtained distributions took the form of log-normal distribution, therefore those two parameters, $d_{Fg}$ and $\sigma_{gdF}$, were determined by fitting the experimental data of the fiber diameters, $d_F$, to the normalized cumulative log-normal function given as follows:

$$G(d_F) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\ln\left(\frac{d_F}{d_{Fg}}\right)}{\sqrt{2} \cdot \ln(\sigma_{gdF})} \right) \right], \quad (1)$$

The normalized density distribution function is described by:

$$g(d_F) = \frac{1}{\sqrt{2\pi d_{Fg}\ln(\sigma_{gdF})}} \exp \left[ -\frac{\ln^2\left(\frac{d_F}{d_{Fg}}\right)}{2\ln^2(\sigma_{gdF})} \right]. \quad (2)$$

Experimental Test Bench MFP Nano

The three previously described fibrous fabrics were tested for effectiveness of the filtration of liquid and solid nanosized particles. For this purpose, a new, advanced test bench MFP Nano (Modular Filter testing rig) was designed and developed by the German manufacturer Palas in cooperation with the Faculty of Chemical and Process Engineering of the Warsaw University of Technology (Fig. 3). In the course of the research, the test bench was modified due to unsatisfactory results, namely the generation of oversized particles (nanosized particles were required) and insufficient dryness of the particles, which led to premature clogging of the equipment. To solve this problem, a new generator followed by a set of three impactors and a drying column filled with silica gel was used. Such properly selected and connected elements, i.e., UGF 2000 particle
generator, impactors, drying column, aerosol neutralizer, U-SMPS, pneumatic filter holder, dilution columns, were paired with software that allowed to constantly control the process to get reliable and repeatable measurement results. The MFP Nano test bench was supplied with compressed air initially purified on an absolute filter and then fed to an UGF 2000 particle generator that can produce liquid and solid nanoparticles from aqueous solutions. It consists of a binary nozzle to adjust flow rate, an integrated streaming pump and a cyclone collector for separating large particles. Then a stream of generated aerosol flows through an assembly of three cascade impactors where particles with diameters greater than submicrons are removed and the stream is then supplied to a drying column, in the case of solid particles. For liquid nanoparticles, the aerosol stream is fed directly to a Kr-85 aerosol neutralizer. Kr-85 is a bipolar neutralizer with a closed source of radiation based on the noble gas Krypton-85, where in the ionization process, β radiation generates positive and negative ions. If mixed with an aerosol stream, the ions are balanced, which is necessary.
for particle counters to make measurements. To measure number and size of nanoparticles, a two stage system was applied called the U-SMPS. For particle size determination Differential Electrical Mobility Classifier (DEMC) was used. Particles flowing out the DEMC column are counted via Universal Fluid Condensation Particle Counter (UF-CPC). The DEMC control unit and the CPC counter are connected together and a signal is transmitted from one device to another via computer. The system is equipped with suitable software to combine the data (i.e., voltage, particle number) to produce a particle size distribution. Particles are classified in the DEMC column based on the differences in their electrical mobility that is directly related to their size. Between the electrodes (internal (+) and external (-)), an electric field is generated whose voltage changes continuously in the process. Depending on the instantaneous value of the voltage, particles of different diameters leave the column. Following the classification stage, the aerosol is directed onto the filter material with a surface of approx. 150 cm$^2$ located in a pneumatic holder. Since only one measurement probe is available in the system, the quantity and the size of the particles that are generated without a filter is initially measured, and then the filter is placed in the holder to measure the values after the filter. A sample of purified air stream is taken after the filter. Then, after passing through the dilution columns with different dilution factors (10; 100; 1,000; 10,000), the sample is directed to a condensation particle counter UF-CPC. In the saturator that is the first section of the UF-CPC counter, the aerosol stream passes through butanol vapor which condenses on the surface of solid particles fed to a section with lower temperature. This is used to increase the size of aerosol particles, which provides a higher precision of the measurement of particle diameters with an optical detector.

**Solid and Liquid Nanoaerosols**

For the purpose of the research, nanoparticles produced in the UGF 2000 generator were potassium chloride (KCl) particulates and liquid particles of DEHS (di-ethyl-hexyl-sebacat) oil. These substances are recommended in filtration effectiveness test standards (EN 779: 2012, EN 1822: 2009). Solid KCl nanoparticles were generated from 0.1% aqueous KCl solution, whereas oil mist from 0.03% solution of DEHS in pure isopropanol. Conditions for the generation of solid and liquid particles were provided so as to get possibly similar their diameters (Fig. 4). The diameters of the produced particles ranged from approx. 20 nm to 200 nm with the majority of them in the range between 30 nm and 60 nm. It was decided to generate polydisperse nanoaerosol streams, as such aerosols are usually emitted by real sources, including diesel engines or produced in various processes, such as combustion, and finally such particles are produced in natural processes, such as volcanic eruptions. Moreover, monodisperse aerosols are more prevalent in published research papers (Mullins et al., 2003; Kim et al., 2006; Mouret et al., 2009).
The observation of nanoscale objects requires hi-tech research equipment that offers high resolution images. Therefore, in order to confirm that the test bench generated and counted solid nanoparticles, the following experiment was conducted. The filter material was replaced with a piece of copper grid with a diameter of 3 mm which “caught” particles obtained from 0.1% aqueous solution of KCl (Fig. 5(a)). Then the grid was analyzed with a Hitachi S5500 scanning transmission electron microscope which captures electrons passing through very thin samples. As seen in Fig. 5(a), individual nanoparticles were generated from aqueous solution of KCl. By analyzing the images from the entire grid, it could be observed that the shape of the nanoparticles was similar to cubes, which is also clearly seen in the images of particles deposited on filter fibers. Fig. 5(b) shows KCl nanoparticles deposited on melt-blown fibers in scanning electron microscope images. The cubical shape of individual generated salt crystals can be seen in the photos. They cover the surface of the fibers evenly without binding or creating dendritic structures, as is the case of larger particles. The mechanism of the deposition of KCl crystals on the surface of polypropylene fibers and their interactions have been extensively investigated by our research team and will be described in another publication.

EXPERIMENTAL RESULTS

Using the MFP Nano test rig, it was examined how three different polypropylene filter mats produced for the purpose of this research paper separated solid and liquid nanoparticles from the air. In addition, the influence of the velocity of aerosol flow through the filter and particle morphology on the efficiency of the separation of the particles from a stream of air was examined.

For each filter, the filtration efficiency and pressure drop were established. Measurements that lasted 1080 seconds (320 s. upstream, 60 s. pause, 320 s. downstream, 60 s. pause and 320 s. upstream once again) were taken at three different flow velocities ($u = 0.05; 0.1$ and $0.2 \text{ m s}^{-1}$) of aerosols passing through the filter material. Each type of fibrous fabric was tested three times in the conditions for the two types of aerosols, and the obtained results were averaged. In order to prove the reproducibility of the obtained data in Fig. 6 are shown the fractional efficiency measurement results of three samples of F5 filter for the filtration of KCl nanoparticles and three samples of F5 filter for the filtration of DEHS liquid nanoparticles with their average values. The obtained results are very similar, which proves the operational stability of the test rig as well as a properly developed measurement procedure. Therefore all the charts included in this paper present averaged parameter values from three measurements. On the plots the fractional efficiency was presented (Figs. 7–9) and in the table the total numerical and mass efficiency and pressure drop (Table 2) were collected.

On the basis of the results obtained in the tests of the nanofiltration process in three melt-blown polymer fibrous filters of different structures produced by the researchers, the following conclusions can be drawn:

1. The separation efficiency for the analyzed range of particle diameters decreases with an increase in the velocity of aerosol with both solid and liquid particles passing through the filter for all tested filters (Fig. 7). Any increase in flow velocity through the filter leads to an increase in flow resistance (Table 2).

2. By reducing the diameter of fibers in the filter mat, it is possible to increase the efficiency of the separation of both solid and liquid nanoparticles from the air (Fig. 8). It is also associated with higher pressure drops observed on the filter (Table 2).

3. By comparing the filtration efficiency of cubical KCl solid nanoparticles and spherical DEHS liquid nanoparticles, it can be noticed that they are very similar (Fig. 9). It means that the shape of nanoparticles does not play any significant role in the process of particle separation from gas as it does in the case of larger particles.

4. For the process parameters applied in the tests, it was
observed that filtering efficiency decreased as the diameters of the particles increased in each analyzed case. This is related to the influence of the diffusion mechanism that tends to decrease with an increase in the diameter of the particle and the growing influence of the mechanism of direct interception. For the tested range of particle diameters, no minimum efficiency which corresponds to the most penetrating particle size (MPPS) was noticed.

THEORETICAL DESCRIPTION

Two approaches: classical theory of nanoparticle filtration applied to the arithmetic mean fiber diameter and the complex Partially Segregated Flow Model for a polydisperse fibrous filters that takes into account the entire fiber size distribution were applied.

According to the classical theory of depth filtration of aerosols in fibrous filters, the deposition of particles with
wherein particle diameter and factor related to the particle Knudsen number (Kn) be determined on the basis of the following formula:

\[ \alpha = 2^{1/3} \left( \frac{1}{3} \right)^{2/3} \left( \frac{d_F}{D} \right)^{1/3} \]  

For an individual fiber with a diameter \( d_F \) diffusion coefficient of an aerosol particle. It can practically negligible, unless there is electrostatic interaction mechanisms (direct interception, inertia, sedimentation) are Brownian motion (diffusion mechanism), while other nanometric diameters is completely controlled by the Cunningham slip correction factor. The latter values (\( a_{Cc} = 1.142, b_{Cc} = 0.558, d_{Cc} = 0.999 \)) were chosen to perform calculations within the framework of this work.

The conversion of the efficiency of an individual fiber into the total efficiency of the filter was carried our using the following expression:

\[ \eta = 1 - \exp \left( \frac{-44E_{el}L}{\pi d_F (1 - \alpha)} \right) \]  

The classical theory presents a significantly simplified approach to filtration issues. It states that each collision of a particle with a fiber is effective and leads to permanent separation of a particle from the air stream. Moreover it assumes that the structure of the filter medium is homogeneous - all fibers with identical diameters are evenly arranged in a plane perpendicular to the direction of aerosol flow. There are some evidence in the literature of the subject that such a description is satisfactory for structurally homogeneous filters composed of identical fibers (Heim et al., 2005; Boskovic et al., 2007; Yun et al., 2007). Notwithstanding, it fails in the case of real polydisperse fibrous filters made of fibers with different diameters, as clearly seen in Fig. 10. Such discrepancies can stem from the heterogeneous filtration structure and the possible phenomenon of particles bouncing off the surface of the filters. Therefore, in the next step, an attempt was made to describe the results obtained from the separation of polydisperse solid and liquid nanoaerosols from the air stream with the Partially Segregated Flow Model (PSFM) proposed by our research group, which was successfully validated by us for solid monodisperse aerosol particles (Podgórski et al., 2011). Unlike the classical theory, where only one fiber diameter (the arithmetical mean diameter in this case) is considered, our model takes into account the entire distribution of fiber diameters. As previously shown, the distributions of diameters of melt-blown fibrous filters could be well described with the log-normal distribution using the density of this distribution for calculations. PSFM is a

### Table 2. Total numeral and mass efficiency of the filtration of KCl solid particles and DEHS liquid particles and pressure drops observed on three different filters at three air velocities.

| Face velocity | Overall numerical | Overall mass | Overall numerical | Overall mass | Overall numerical | Overall mass |
|---------------|------------------|-------------|------------------|-------------|------------------|-------------|
| KCl           |                  |             |                  |             |                  |             |
| \( u = 0.05 \text{ [m s}^{-1}] \) | 91.19 | 76.09 | 83.18 | 57.35 | 68.76 | 37.42 |
| \( u = 0.10 \text{ [m s}^{-1}] \) | 82.92 | 64.89 | 63.63 | 40.96 | 32.36 | 16.47 |
| \( u = 0.20 \text{ [m s}^{-1}] \) | 78.64 | 61.57 | 43.87 | 26.71 | 32.31 | 15.29 |
| DEHS          |                  |             |                  |             |                  |             |
| \( u = 0.05 \text{ [m s}^{-1}] \) | 84.38 | 65.11 | 76.10 | 44.54 | 49.54 | 23.95 |
| \( u = 0.10 \text{ [m s}^{-1}] \) | 71.28 | 53.72 | 66.18 | 34.95 | 38.39 | 17.03 |
| \( u = 0.20 \text{ [m s}^{-1}] \) | 67.44 | 53.09 | 62.50 | 30.74 | 26.70 | 12.08 |
| Pressure drop [Pa] |              |             |                  |             |                  |             |
| \( u = 0.05 \text{ [m s}^{-1}] \) | 20.27 | 10.42 | 6.85 |
| \( u = 0.10 \text{ [m s}^{-1}] \) | 42.56 | 21.84 | 11.56 |
| \( u = 0.20 \text{ [m s}^{-1}] \) | 84.94 | 46.18 | 15.66 |
Fig. 7. Influence of aerosol velocity on the efficiency of removal of KCl solid and DEHS liquid nanoparticles from the air for three tested melt-blown filters: (a) and (b) filter F10, (c) and (d) filter F5, (e) and (f) filter F0.5.

The combination of limiting models of the Fully Segregated Flow Model (FSFM) and the Perfectly Mixed Flow Model (PMFM) that respectively estimate above and below possible values of filtration efficiency:

\[ \eta_{\text{FSFM}} = s(1 - \eta_{\text{FSFM}}) + (1 - s)(1 - \eta_{\text{PMFM}}). \]  

(7)

The coefficient \( s \) (flow segregation intensity) in Eq. (7) describes the nature of the flow of particles in the filter. It must be determined on the basis of experimental data of filtration efficiency. Limiting models are calculated taking into account all mechanisms affecting a particle, but in the case of nanoparticles it is limited only to the diffusion mechanism. The efficiency for PMFM and FSFM takes the form respectively:

\[ \eta_{\text{PMFM}} = 1 - \exp \left[ -\frac{4\alpha L}{\pi(1-\alpha)} \left( \frac{E_d(d_F)}{d_F} \int_0^{d_F} g(d_r) \, dd_r \right) \right], \]

(8)
Fig. 8. Influence of the morphology of three fibrous filters on the efficiency of removal of KCl solid and DEHS liquid nanoparticles from the air for three aerosol velocities: (a) and (b) $u = 0.05$ [m s$^{-1}$], (c) and (d) $u = 0.10$ [m s$^{-1}$], (e) and (f) $u = 0.20$ [m s$^{-1}$].

(a) and (b) $u = 0.05$ [m/s]  (c) and (d) $u = 0.10$ [m/s]  (e) and (f) $u = 0.20$ [m/s]  △ F10  □ F5  ○ F0.5

$\eta_{PSFM} = 1 - \frac{\int d_F \eta(d_F) g(d_F) \, dF}{\int d_F g(d_F) \, dF}$,  \hspace{1cm} (9)

where $\eta(d_F)$ denotes the efficiency calculated from Eq. (6).

The discrepancies observed in Fig. 10 between the experimental data and the results of the calculations based on the classical theory are believed to be due to the heterogeneity of the filter media, because the results obtained from the PSFM model describe well the obtained data. It also suggests that the tests were conducted without particle bouncing off the surface of the fibers, the phenomenon which depends on the material of the fiber as well as the particle, and the speed and size of the latter (Hinds, 1999).

**CONCLUSIONS**

In the framework of this work it has been shown that
three fibrous filters with different structures produced by us using melt-blown technology can efficiently remove solid and liquid polydisperse nanoparticles from the air. It is evident that the technology of blowing the molten polymer offers endless possibilities for developing filters of particular structure, and allows us to produce fibers with a wide range diameters, including nanometric fibers obtained in electrospinning. The melt-blown technology facilitates manufacturing large quantities of fibers at reduced cost, which definitely increases their application value, compared to electrospun fibers. Moreover, the method of reliable testing the nanoparticle filtration was improved.

It turned out that at the lowest tested velocity of aerosol flowing through the filter, the nonwoven filter material made of nanofibers showed the greatest efficiency. It should be borne in mind that a decrease in fiber diameter results in an increase in pressure drop across the filter, mainly due to the resistance of individual fibers to flow. Moreover, pressure drop is also proportional to the face velocity, because the flow in the filter is laminar. Therefore, when designing a material for nanofiltration, two main parameters that must be considered together to obtain the maximum efficiency at relatively low gas flow resistance are efficiency and pressure drop. Using a mixed filter composed of nano- and microfibers blended together in it seems to be a good solution. Nanofibers will ensure high particle capturing efficiency, whereas thicker fibers will prevent too high pressure drop. The concept of the development of such filters will be presented in another paper.

On the basis of the obtained results, there is no clear effect of the morphology of separated nanoparticles on the efficiency of the filtering process. For the investigated range of diameters of both solid KCl and liquid DEHS nanoparticles, the efficiency of capturing them by the filter fibers is similar. Under applied experimental conditions, the filtration efficiency decreases with increasing particle diameters.

The experimental findings concerning nanofiltration were explained using the classical filtration theory and a mathematical model called the Partially Segregated Flow Model formulated by our research group. As a result, the actual, experimentally determined filtration efficiency proved to be lower in each of the analyzed cases than that calculated theoretically based on the classical theory. This is the consequence of simplifying assumptions of the theory about the homogeneity of the filter structure which is in fact polydisperse (uneven distribution of fibers of various diameters). This is confirmed by the good approximation of the obtained results of nanofiltration in melt-blown filters based on the PSFM model that takes into account the entire distribution of the diameters of fibers. It turned out that this model is suitable to describe the filtration of not only submicron- and micron-sized particles but also solid and liquid nanoobjects.

**Fig. 9.** Influence of the morphology of particles on the efficiency of their removal from the air for three aerosol velocities: (a) $u = 0.05 \, [\text{m s}^{-1}]$, (b) $u = 0.10 \, [\text{m s}^{-1}]$, (c) $u = 0.20 \, [\text{m s}^{-1}]$. 

KCl and DEHS particles

(a) $u = 0.05 \, [\text{m s}^{-1}]$

(b) $u = 0.10 \, [\text{m s}^{-1}]$

(c) $u = 0.20 \, [\text{m s}^{-1}]$

- F10, KCl particles
- F5, KCl particles
- F0.5, KCl particles
- F10, DEHS liquid particles
- F5, DEHS liquid particles
- F0.5, DEHS liquid particles
Fig. 10. Comparison of experimental values of the filtration efficiency (points) with results of calculations obtained using the classical theory (solid lines) and PSFM model (dashed lines) for: (a) Filter 10, KCl particles, (b) Filter 10, DEHS particles, (c) Filter 5, DEHS particles and (d) Filter 0.5, DEHS particles.

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