Separation of nanoparticles and nanodroplets from air using fibrous filters

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Separation of particles from gas stream is of great importance in many areas of human life. Air filtering materials have wide applications. They are used inter alia in ventilation and air conditioning systems, in cars to reduce emission from diesel engines, in the device of everyday use (e.g. vacuum cleaner), as a personal protective equipment for example to avoid inhalation hazardous dust from industrial processes. Small airborne particles can cause a variety problems for human health. Long exposure to particles of submicron- and nano-sized has been related to higher death rates due to lung cancer and cardiopulmonary illness. The main object of this study was to investigate filtration efficiency of oil nanodroplets (DEHS di-ethylhexyl sebacate) and salt nanoparticles (KCl) from air using fibrous polypropylene media made by melt-blown technique. Fibrous filters are relatively inexpensive to fabricate and what is the most important they are high efficient with simultaneous low flow resistance. Three types of non-wovens having various morphology with different average fiber diameter were tested. The tests show that both KCl solid nanoparticles and DEHS nano oil-mist can be efficiently separate from the air using melt-blown fibrous materials. Moreover these filters have been also electrically charged by corona discharge. The filtration efficiency of charged filters (electrets) was compared with efficiency of uncharged (mechanicals) samples. Results showed significant increase in filtration efficiency for the filters with electric charge compared with uncharged ones.
Key words: electrets, fibrous filters, filtration, nanodroplets, nanoparticles

Introduction

Among a large number of devices for protection human health and environment nonwoven filters are very attractive ones. Their advantages are versatility, low cost and environmentally friendly production. These media can separate various particles from air, also nanoparticles, which due to their size may have negative impact on health. They penetrate into the deepest parts of the lungs from where it could even go into the bloodstream and next accumulate in the organs such as kidney, liver, testis, ovary, heart and spleen [W.G. Shina, et.al, 2008]. Liquid nanoaerosols (e.g. oil-mist) constitute a significant part of atmospheric pollution and they are also formed in many technological processes. This oil-mist sometimes contains metals or products of combustion and harmful carcinogens [T. Jankowski, 2009]. Due to the risk that is associated with nanoparticles the rules governing their concentration in the air are increasingly restrictive. Therefore they effective separation is very important issue. The literature contains a number of papers about filtration of submicron aerosols but very few about nanoaerosols. This is because of the fact that both generation and detection of such small objects are difficult in laboratory conditions. The special, high quality measuring equipment should be applied in experimental procedure.

Throughout the world researchers are doing investigations into modification of the filtering materials to increase their strength, flexibility, change wettability and adhesiveness. It may be carried out at the stage of material forming as well as modifying in various ways the finished material. Depending on what effect is desirable different methods influencing the properties of the separating material are sought [D. Knittel et. al., 2000]. The higher efficiency of fibrous filters can be achieved by giving them an electric charge what causes the increase in separation rate without increasing in pressure drop across the filter what was discussed by Chazelet et. al. (2011).

In this work very important subject was undertaken concerning separation of different nano-objects from air using non-woven filters. It was also examined whether charging the fibres has an impact on their effectiveness.

Experimental methods

All filtration tests have been done on MFP nano Plus test bench produced by PALAS GmbH company. Scheme of this equipment is presented in Figure 1.

Aerosols used in experimental procedure were produced by the UGF 2000 generator which is able to atomize liquid (DEHS di-ethylhexyl sebacate) as well as solid particles (KCl). Both types of particles are recommended by the standards for the filtration tests. The UGF 2000 comprises a binary nozzle for adjustment of the desired mass flow and also a cyclone with built-in control air system. After leaving the UGF particles go through three impactors to cut off rest of large particles and leave only nano-sized ones.

To measure the size distribution and concentration of nanoparticles and nanodroplets, a two-stage process was

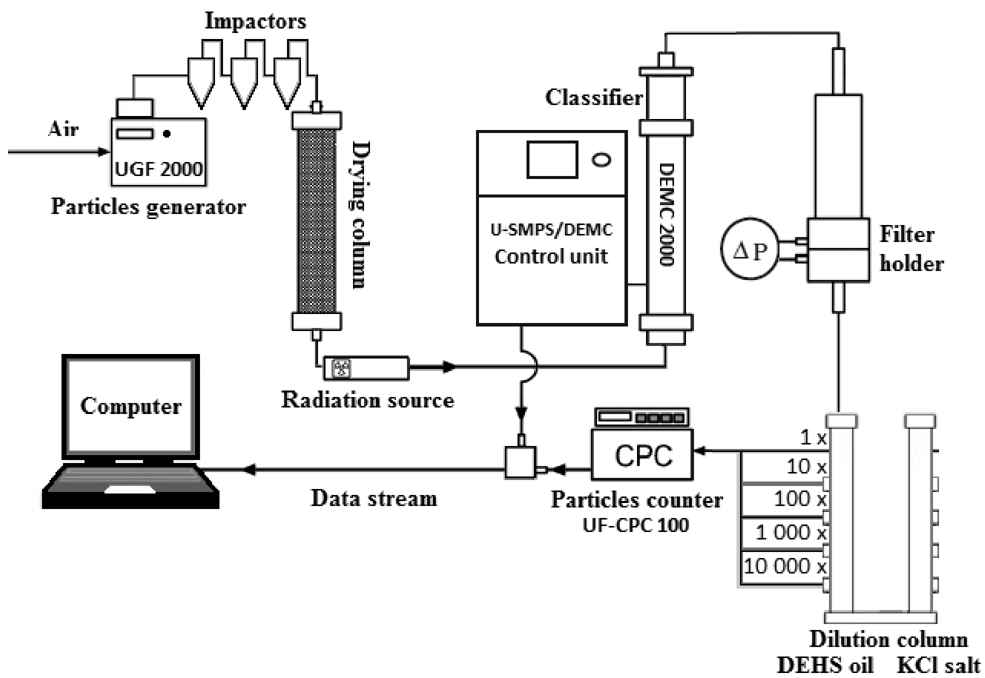

Figure 1. Scheme of the test bench for nanofiltration experiments

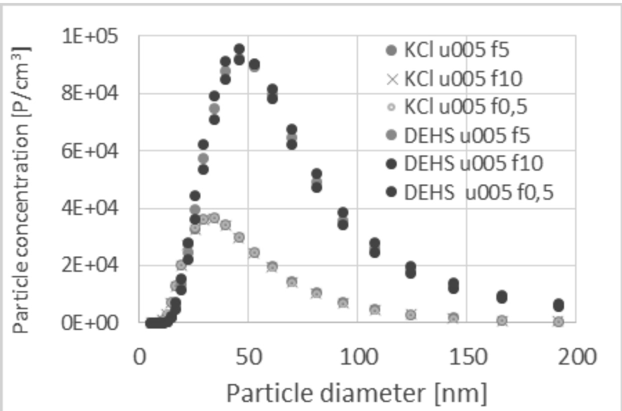

Figure 2. Size distribution of generated KCl and DEHS nanoparticles at air velocity u = 0,05 m/s

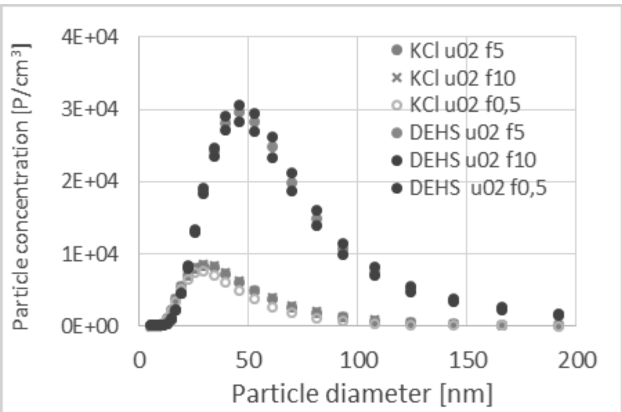

Figure 3. Size distribution of generated KCl and DEHS nanoparticles at air velocity u = 0,2 m/s

applied. A unique system composed of a Differential Electrical Mobility Classifier (DEMC) with a Universal Fluid Condensation Particle Counter (UF-CPC) was utilized. In DEMC particles are classified according to their electrical mobility. During measurement voltage in column is changing continuously. The charged particles are introduced into a radially symmetric electric field, which is produced by applying voltage between a positively charged inner electrode and earthed outer electrode. Particles have a certain mobility so, if the voltage is subsequently changed, particles with a different mobility pass through the gap and can subsequently be counted. In UF-CPC aerosol enters to the first heated evaporation chamber with working fluid. The saturated carrier gas enters to second chamber – a cooled region, where a working fluid condenses onto nanoparticles. This procedure allows to enlarge particles to sizes larger than 1 m. After the condenser the particles enter the optical sensor.

During experiments the filtration efficiency and the pressure drop were determined for three types of filters. The investigations have been done for two different aerosol face velocities of u = 0,05 m/s and u = 0,2 m/s. Concentration of particles was different for each velocities. Concentrations for u = 0,05 m/s equal:

$C_{DEHS} = 2{,}55 \cdot 10^5$ P/cm³

$C_{KCl} = 7{,}12 \cdot 10^4$ P/cm³

and for u = 0,2 m/s:

$C_{DEHS} = 8{,}07 \cdot 10^5$ P/cm³

$C_{KCl} = 3{,}27 \cdot 10^5$ P/cm³.

Size distributions of particles are presented in Figure 2 and Figure 3.

Each filtration efficiency test has been carried out under the same duration. The time of particle measurement before (upstream) and after (downstream) the filter took 350 seconds. Three samples of each filtrating material.

Experimental objects

The experimental objects were three different polypropylene filters with various mean fiber diameters (Filter 10, Filter 5, Filter 0,5). SEM images of these media are presented in Figure 4. All of them were made by us using the melt-blown technique which allows to produce fibrous filtrating materials with defined structure, i.e. porosity, thickness and fiber diameter. More information about filter media characterization and production were published by [A. Jackiewicz et al. 2013]. Filters 10 have thickest average

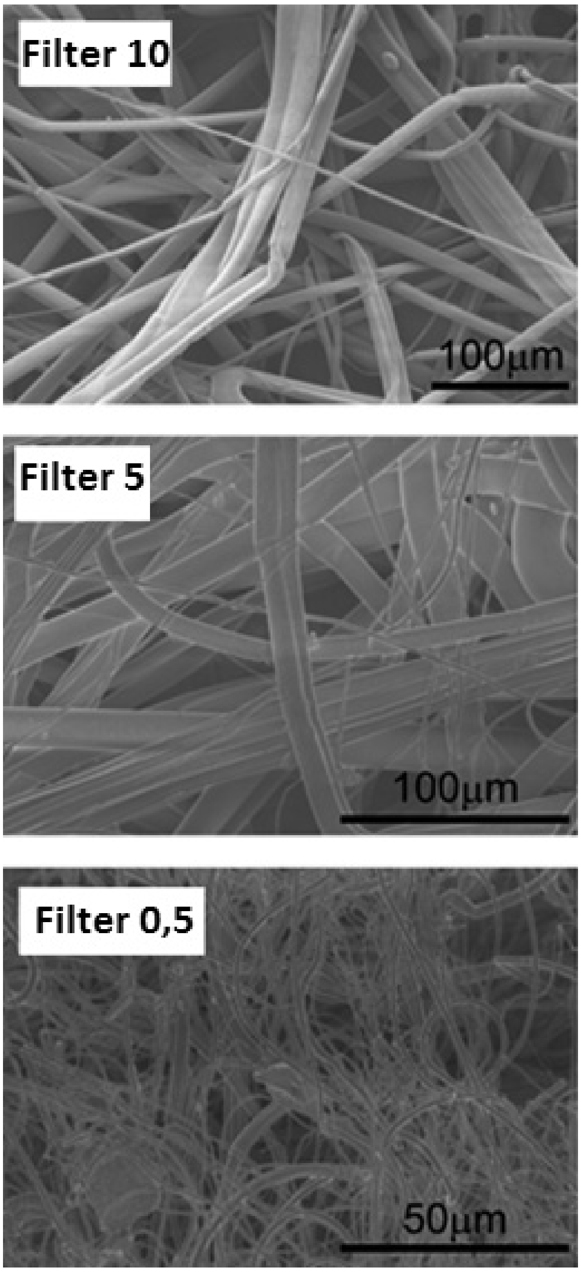

Figure 4. SEM images of three different melt-blown filters: Filter 10, Filter 5 and Filter 0,5

Table 1. Mean fiber diameters of the tested filters

Filters	Arithmetic mean fiber diameter d_{Fa} [µm]	Standard deviation σ_{adF} [µm]
Filter 10	8,99	0,76
Filter 5	5,60	0,99
Filter 0,5	0,47	0,83

Table 2. Structural parameters of the tested filters

Filter	Filter thickness L [mm]	Filter solidity α[-]	Basis weight q_s [g/m^2]
Filter 10	2,98	0,105	282,9
Filter 5	1,81	0,072	117,1
Filter 0,5	1,75	0,029	54,9

fiber diameter and lowest porosity and by analogy Filters 0,5 have thinnest average fiber diameter and greatest porosity. The structural parameters of the tested filters are presented in Tables 1 and 2.

In the next step, to improve the separation efficiency of nanoparticles in fibrous filters an electrostatic interaction between the particles and fibers were involved. The electrostatic forces which intensify the process of filtration are: columbic forces – when a particle and a fiber are charged and the induced forces – when a charged fiber induces on the surface of an inert particles opposite sign charge and in the results they are attracted each other. In the case of our research the second phenomenon was investigated. The experimental studies for filtration of submicron and micron particles in electret filters were published by Jackiewicz and Gradoń, (2011). Three mechanical filters with neutral fibers 10, 5 and 0,5 were charged by corona discharge when molten polymer was blown out from the die by using a comb electrode placed next to the nozzle. The distance between the electrode and a collecting electrode was 45 mm. Both electrodes were located at a distance of 60 mm below a nozzle with melted polymer. The average voltage during the charging was 32,9 kV and average amperage was 0,32 mA. To show the effect of electrostatic mechanism on nanoparticle separation the results of filtration efficiency for electret filters were compared with the results of filtration efficiency for filters without charge. Both types of nonwoven filters were almost identical in their structure, therefore it was easy to show the influence of electrostatic mechanism on the effectiveness of nanofiltration

Results

For each type of filter medium the pressure drop across the filter and the efficiency of filtration were determined. These two parameters are crucial for evaluation separation media. Measurements were carried out for two types of nanoparticles – solid and liquid – for two air velocities of 0,05 m/s and 0,2 m/s.

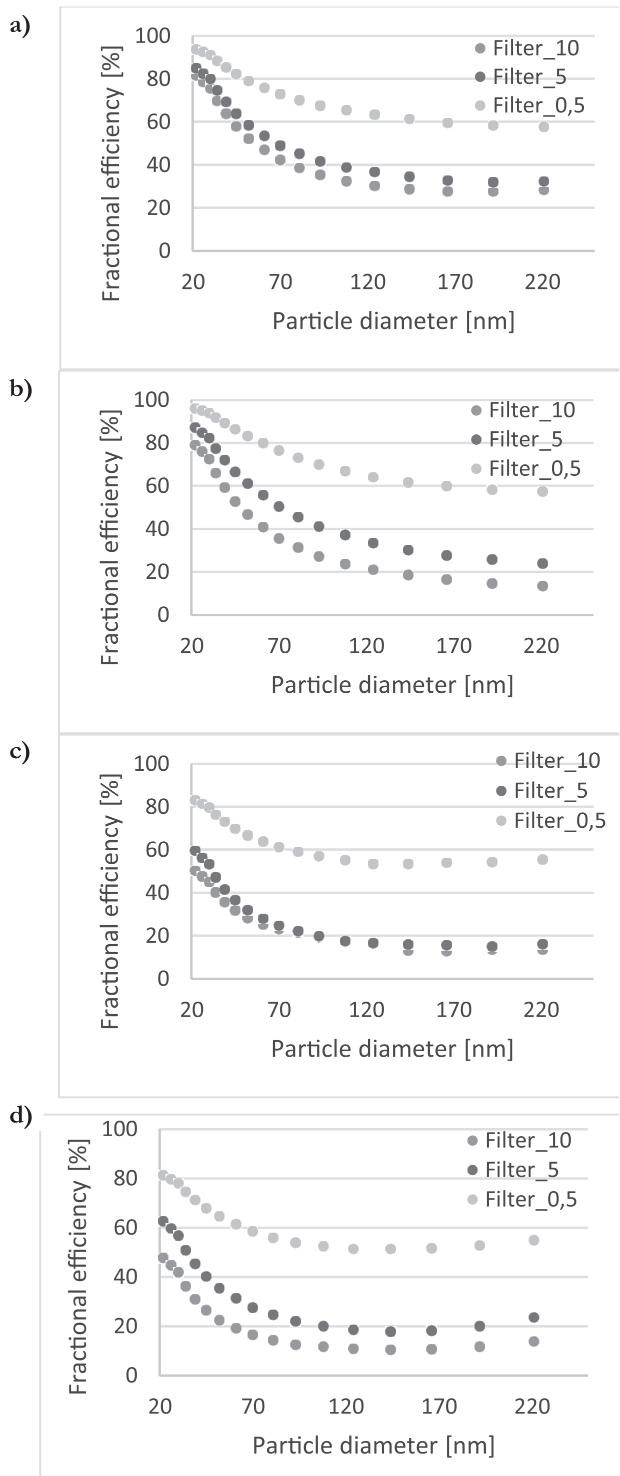

Figure 5. Fractional efficiency of removal from the air
a) Solid nanoparticles (KCl) at face velocity υ = 0,05 m/s
b) Liquid nanodroplets (DEHS) at face velocity υ = 0,05 m/s
c) Solid nanoparticles (KCl) at face velocity υ = 0,2 m/s
d) Liquid nanodroplets (DEHS) at face velocity υ = 0,2m/s on three polypropylene uncharged (mechanical) filters with different morphology

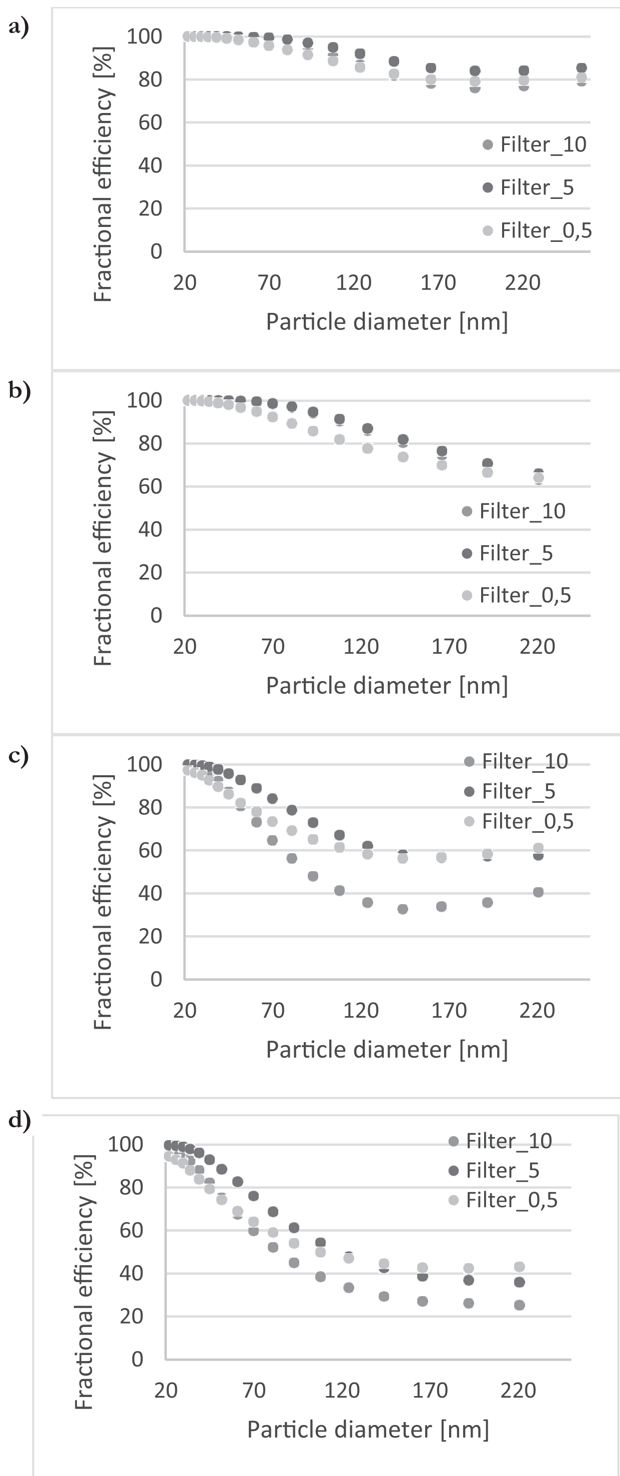

Figure 6. Fractional efficiency of removal from the air.
a) Solid nanoparticles (KCl) at face velocity υ = 0,05 m/s
b) Liquid nanodroplets (DEHS) at face velocity υ = 0,05 m/s
c) Solid nanoparticles (KCl) at face velocity υ = 0,2 m/s
d) Liquid nanodroplets (DEHS) at face velocity υ = 0,2m/s on polypropylene charged (electret) filters with different morphology

Table 3. Pressure drop of the tested filters

u = 0,05 [m/s]	Mechanical filter	Electret
KCl	Pressure drop [Pa]	
Filter 0,5	16,19	8,86
Filter 5	8,54	12,91
Filter 10	4,48	6,48
DEHS	Pressure drops [Pa]	
Filter 0,5	14,98	7,28
Filter 5	5,09	10,7
Filter 10	3,49	4,47

The results of experimental investigations show that both salt nanoparticles and oil nanodroplets can be efficiently separate from the air using melt-blown fibrous materials. It is also easy to notice that filter structure affects its performance. It was found that for mechanical filters a significant increase in filtration efficiency can be obtained by applying nanofibrous materials, i.e., Filter 0,5 (Fig. 5). The thicker the fibers in a filter are the lower fractional efficiency filter has. It can be noticed in Figs 5 and 6 that for all investigated materials the filtration efficiency decreases with increase the particle diameter.

Based on these results it can be seen that for lower aerosol velocity (u = 0,05 m/s) the obtained filtration efficiency is higher than for higher aerosol velocity (u = 0,2 m/s).

Moreover, comparing results of filtration efficiency for the charged (electret) and neutral filters having very similar structures it is clear that in each case the filtration efficiency of electret filter is much higher (see Figs 5 and 6). The charging of the fibers bring the desired effect, taking also into account that the increase of effectiveness has not been paid with the increase in the pressure drop as shown in Table 3. The observed discrepancies between values are caused by the nonuniformity of the flat filter mat from which the analyzed samples are cut out. The thinner fibers filter has the greater heterogeneity can be seen in its structure, which is reflected in the resulting values of the pressure drop (Table 3).

Conclusions

In the framework of this work it has been shown that the nonwoven filters produced using the melt-blown technology are highly efficient for removing solid and liquid polydisperse nanoparticles from the air. Analyzing the influence of the process conditions turned out that in the case of lower aerosol velocity the filter performance are better (higher nanoparticles separation efficiency and lower pressure drop).

On the basis of the obtained results, it can be seen that designing a filter with thinner fibers one can greatly increase the separation efficiency of the aerosol nanoparticles in comparison with filters composed of thicker fibers. The experimental data show also that a decrease in fiber diameter results in an increase in value of pressure drop across the filter, because of the resistance of individual fibers to flow.

It was proven that electric charges on fiber enhance the separation efficiency for both types of analyzed particles without great increase in pressure drop. The obtained discrepancy are attributed to the nonuniformity of the filter mat.

Furthermore, as opposed to the bigger particles, there is no influence of the nanoparticle morphology on the filter effectiveness. Both cubic solid and spherical liquid nanoparticles are removed from air stream with similar efficiency.

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