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Filtering of DEP (Diesel Exhaust Particles) in Fibrous Filters

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Nowadays half of all cars are equipped with diesel engine and this number is still increasing. In 2012 IARC (International Agency for Research on Cancer) classified diesel exhaust as carcinogens to humans. Diesel exhaust particles (DEP), solid phase of diesel exhaust fumes, are the major compound of air pollutant. Popular device used to purifying air is fibrous filter, however, the information about DEP filtration in fibrous filters is scarce. Therefore, the goal of this study was to compare filtration efficiency of fibrous filters with different mean fiber diameter exposed to diesel exhaust particles from three commercially available diesel fuels. High effectiveness fibrous filter can be used in particulate-filtering respirators or in cab car to protect against DEP.
The highest filtration efficiencies were obtained for fibrous filter with 8.18 μm mean fiber diameter (98.5 %, 95.7 %, 97.8 % for various DEP). Furthermore, the results show that small (< 100 nm), more spherical in shape aggregates are filtered with higher efficiency than similar in size, but dendrite-like aggregates, regardless of mean fiber diameter of fibrous filters.
Morphology of aggregate (size, shape) and fibrous filter structure strongly influence the DEP filtration efficiency, which can lead to difficulties during, for example, theoretical modeling of DEP filtration process.

1. Introduction

Diesel exhaust particles (DEP) are fractal-like aggregates composed of small particles (primary particles) attached together (Kittelson, 1998). Diameter of DEP is in the range of 10 nm – 2000 nm (Kittelson,1998; Harris and Maricq, 2001). DEP size, shape, adsorbed compounds strongly depend on diesel fuels, engine age etc. (Burtscher, 2005). DEP are believed to be mutagenic and cytotoxic to humans (Pope et al., 2002), since they are a part of diesel exhaust fumes, which IARC (The International Agency for Research on Cancer) classified as carcinogenic to humans. Moreover, a lot of compounds adsorbed on DEP surface are genotoxic (Ono-Ogasawara and Smith, 2004).
Due to the large number of cars equipped with diesel engine, DEP are commonly met in ambient air and workplace (e.g. in car workshop, bus depot). Nowadays, diesel engines are equipped with Diesel Particulate Filter (DPF), however, number of older cars without DPF is still high. Nearly 3 million workers in Europe are exposed to diesel exhaust fumes (Groves and Cain, 2000).
Therefore, DEP capture or removal from the air is essential for health care and environment protection. Fibrous filters are commonly used for air purification, however, they are not tested using DEP aerosol (Wilkes, 2002; Huang et al., 2007; Cho et al., 2011). Due to the complex structure of DEP their filtration in fibrous filter is very rarely topic of empirical studies.
The aim of this research was to find the fibrous filter characterised by high filtration efficiency for various diesel exhaust particles. Such fibrous filter can be used in particulate-filtering respirators or in cab car to protect against DEP.
This study is a continuation of our earlier investigation (Penconek et al., 2013) which showed that the commercially available dust half masks (typically tested using polydisperse sodium chloride and paraffin oil particles) may not ensure a high level of humans protection against DEP, since they filtered only 76 – 89 % of DEP (depending on source of DEP and types of dust half mask).

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2. Materials and methods

2.1 Fibrous filters

The nonwoven fibrous filters have been made from polypropylene using melt-blowing methods. The physical parameters of fibrous filters are summarized in Table 1.

Table 1: Characteristics of fibrous filters

Fibrous filter	Mean fiber diameter, µm	Thickness of layer, mm	Area density, g m^{-2}	Packing density, −
1	12.88	4	249	0.069
2	8.18	4	149	0.083
3	1.43	0.5	30	0.067

The mean fiber diameter (d_f) was obtained with a use of scanning electron microscope (TM-1000, Hitachi, Japan) connected to a digital camera and PC computer. Calliper was used to determine the thickness of each layer (L). The area density (σ_s) was obtained by weighing the samples of filters with a known surface area.
The packing density (d) was calculated as:

$$d = \frac{\sigma_s}{L \cdot \rho_{pp}} \tag{1}$$

where: σ_s is the area density, g m^{-2}; L is the thickness of layer, mm; and ρ_{pp} is the density of polypropylene g·m^{-3}.

The fibers diameter size distributions in fibrous filters are show in Figure 1.

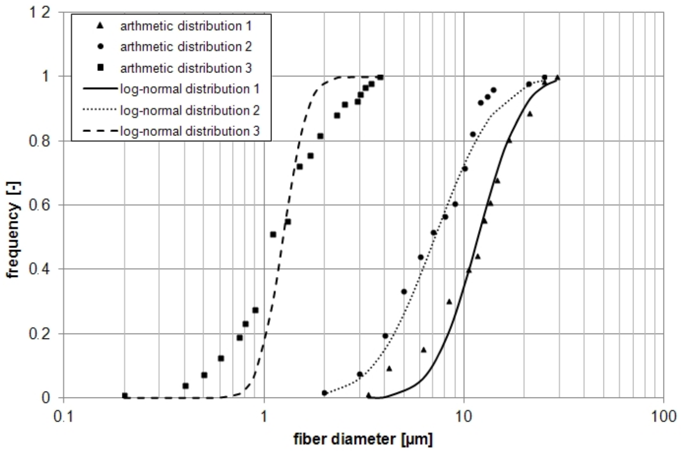

Figure 1: Fiber diameter size distribution in fibrous filters 1, 2, and 3

2.2 Diesel exhaust particles

Diesel exhaust particles (DEP) were generated using Mercedes Benz 240D diesel engine (manufactured in 1982, 4 cylinders, engine power 53 kW at 4200 rpm; torque 137 Nm at 2400 rpm; engine displacement 2399 cm^3). Three different diesel fuels were used to generate DEP. Table 2 summarises the physical characteristics (provided by manufacturers) of the fuels. Motor emissions were generated under idle speed conditions. The humidity (40 - 50 %) and temperature of the air around the diesel engine (20 - 25 °C) was identical during tests. Table 3 summarises the characteristics (CMD – Count Median Diameter, fractal dimension and observed shape) of DEP obtained from three diesel fuels.

Table 2: Characteristics of diesel fuels

	Fuel I	Fuel II	Fuel III
number of compounds*	100	20	184
density at 15ºC, kg/m^3	820 - 845	860 - 900	820 - 845
sulphur content, mg/kg	<10	0	<10
fatty acids methyl esters content, % (v/v)	no data	96.5	5

*Number of compounds was determined by the authors of this study using gas chromatography–mass spectrometry method.

Table 3: Characteristics of DEP

	CMD, µm	Fractal dimension*	Observed shape
DEP from fuel I	0.03	~1.7	Dendrite like
DEP from fuel II	0.06	~2.5	Spherical
DEP from fuel III	0.12	~1.7	Dendrite like

*The value of fractal dimension was only based on DEP pictures without sophisticated algorithm of pictures analysis.

2.3 Experimental set-up

The pressure drop and filtration efficiency were measured with the use of methods similar to those presented in Penconek et al. (2013). Experimental set-up is presented in Figure 2.

The tested fibrous filter has been placed in special holder in the chamber (1 m^3) where diesel exhaust fumes from the engine were directed. Diesel fumes were stabilized in a buffer tank. Diesel engine and buffer tank were situated outside the building. The air flow was generated by the pump (SC10A 055S Venture Industries, Poland) and controlled by electronic flowmeter (4040 model nano, TSI Inc., USA). The pressure drop across tested fibrous filters was measured using DPC-CALC 8710 micromanometer (TSI Inc, USA). Number size distribution of DEP beyond tested fibrous filters was obtained with the use of Fast Automotive Particles Emission Spectrometer - FAPES (Model 5.601, Grimm GmbH, Germany) described in details elsewhere (Penconek et al., 2013).

Motor emissions were generated continuously throughout the test under idle speed (800 rpm) conditions. The test started when the diesel engine oil temperature reached 86 °C (the temperature did not change during the test). The filtration efficiency of DEP and pressure drop across fibrous filters were measured at a constant flow rate of 30 dm^3·min^{-1} during 20-min long inhalation.

The filtration efficiency of DEP was determined gravimetrically as:

$$E = \frac{M_f}{M_f + M_{af}} \cdot 100\% \qquad (2)$$

where: E is the filtration efficiency, M_{af}, M_f is the mass of DEP deposited on the reference absolute filter (*af*) and on tested fibrous filter (*f*) after 20 mins.

The mass of DEP penetrated through the fibrous filters were determined by weighting the absolute filter at each and every 5-min interval of the test. Pressure drop across fibrous filter and the DEP number size distribution beyond fibrous filter were measured continuously throughout the test.

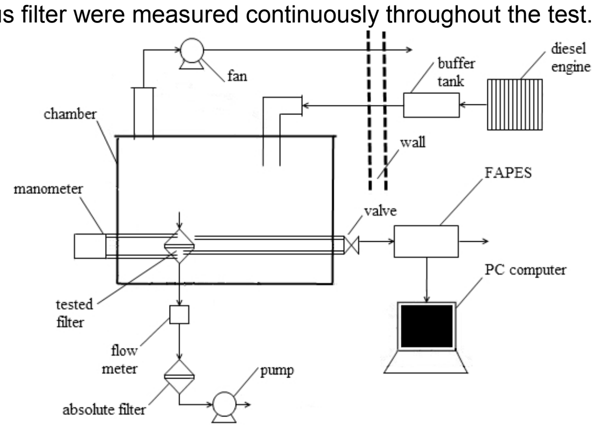

Figure 2: Experimental set-up (based on Penconek et al., 2013)

3. Results and discussion

3.1 Filtration efficiency

Three fibrous filters, characterised by parameters showed in Table 1, were analyzed for different diesel exhaust particles obtained from three commercially available diesel fuels. The mean values and standard deviations were calculated for four samples of each fibrous filter tested in this study.

The filtration efficiency of DEP from fuel I, II, and III for three fibrous filters characterised by mean fiber diameter 12.88, 8.18, and 1.43 µm, respectively are shown in Figure 3.

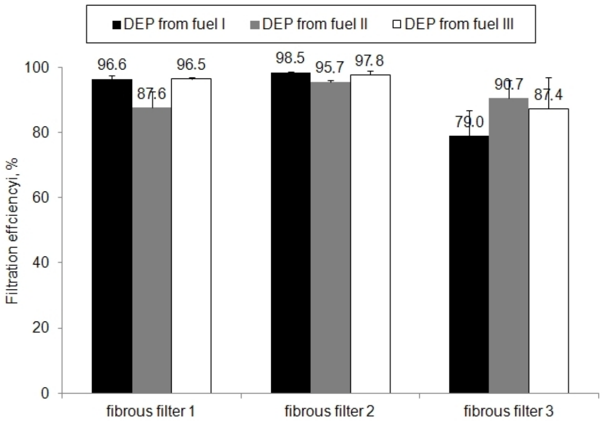

Figure 3: Filtration efficiency of fibrous filters. Columns represent the mean values and error bars represent the standard deviations from the four tests conducted for each fibrous filter

From a visual inspection of the graphs, it can be found that the fibrous filter No. 2 has the highest filtration efficiency of DEP from fuel I, II, and III. It can be seen, however, that values of filtration efficiencies are higher than 95 % (in 6 cases) but lower than 99 % (95 % and 99 % is minimum filtration efficiency required by European Norm (EN 149:2004) for particulate-filtering respirators type 2 and 3, respectively).

3.2 Pressure drop and DEP mass penetration

The pressure drop across fibrous filter (fibrous filter No.1, 2, and 3) and DEP (from fuel I, II, and III) mass penetration through fibrous filter are shown in Figure 4, 5, and 6, respectively. Symbols represent the mean values and error bars represent the standard deviations from the four tests conducted for each fibrous filter and fuel types.

It can be noted that pressure drop across fibrous filter No. 2 is the highest (Figure 4A, 5A, 6A), regardless of DEP types. It is reasonable to expect that high pressure drop is caused by high flow resistance what can be a reason for low DEP mass penetration through fibrous filter No. 2 (Figure 4A, 5A, 6A), and as a consequence, the highest filtration efficiencies (98.52 % for DEP from fuel I, 95.66 % for DEP from fuel II, 97.85 % for DEP from fuel III).

It is worth noting that pressure drop across fibrous filter during the test increases when dendrite-like DEP (from fuel I and III) are filtered but is constant when spherical ones (from fuel II) are examined.

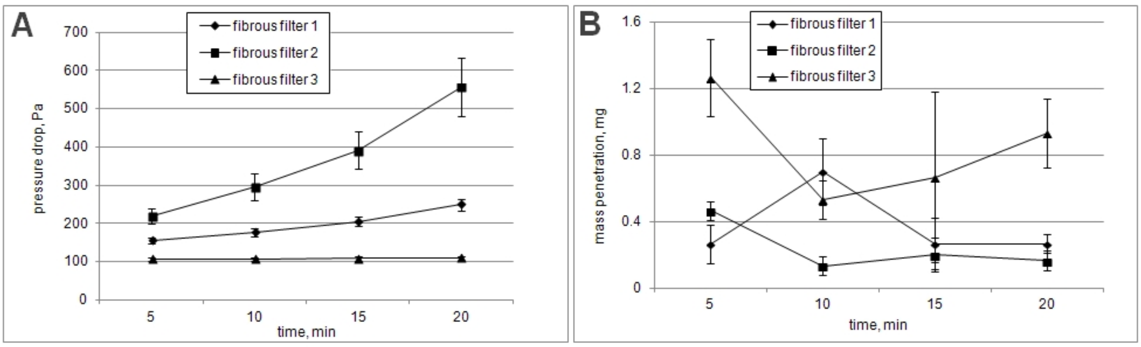

Figure 4: Pressure drop across fibrous filter (A) and mass penetration (B) of DEP from fuel I

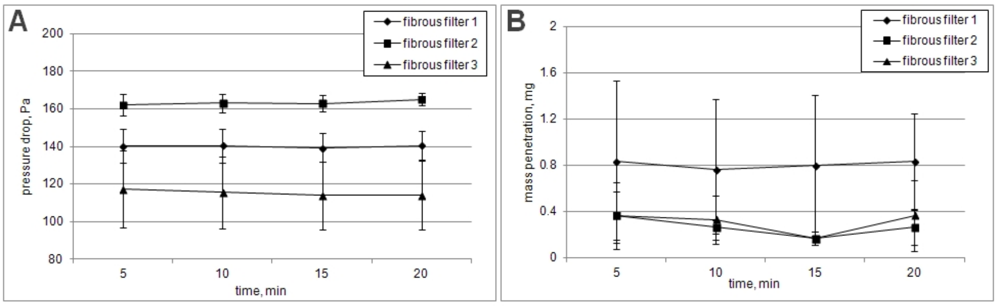

Figure 5: Pressure drop across fibrous filter (A) and mass penetration (B) of DEP from fuel II

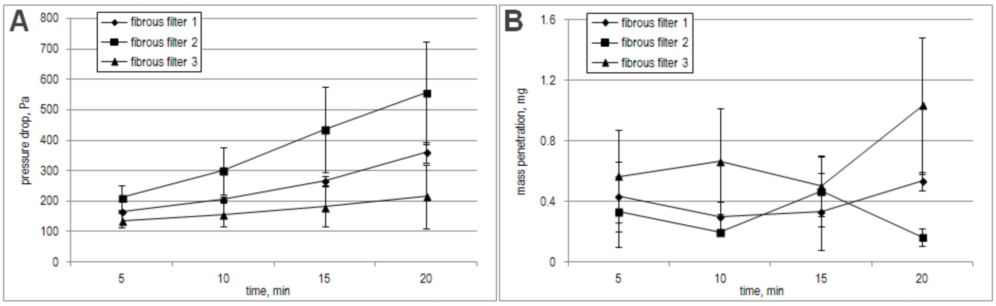

Figure 6: Pressure drop across fibrous filter (A) and mass penetration (B) of DEP from fuel III

3.3 DEP size distribution

Figure 7 shows the DEP number size distribution (based on electrical mobility diameter) in space beyond fibrous filters in 10-th and 20-th min of the test. Number size distribution was obtained using Fast Automotive Particle Emission Spectrometer dedicated to measurement in engine exhaust (e.g. FAPES is equipped with a fully integrated sampling and dilution system, suitable for temperatures of up to 500 °C), however, obtained particles diameter is in the size range of 6 nm to 640 nm, while DEP diameter could be even 2000 nm. Therefore, number size distribution presented in Figure 7 may be not complete.
Nevertheless, it can be found that spherical DEP (from fuel II, Figure 7B) with diameter < 100 nm are filtered with a higher efficiency in all of the tested fibrous filters than dendrite-like DEP with the same diameter (Figure 7A and C).

4. Conclusions

Fibrous filters are usually used for aerosol filtration. Spherical aerosol particles are commonly used to obtain fibrous filter efficiency both in experiments and theoretical calculations. However, in ambient air spherical particles are very rare. On the other hand, studies on filtration process of nonspherical particles in fibrous filter are scarce and mostly theoretical e.g (Bałazy and Podgórski, 2007).
In this study we investigated the usefulness of three different fibrous filters for diesel exhaust particles filtration, since DEP are frequently met in ambient air and in workplace. The results obtained indicate that fibrous filter, characterized by mean fiber diameter of 8.18 μm, eliminates 95 - 99 % of DEP, while two another tested fibrous filters capture 79 – 97 % of DEP. Moreover, the results depict that regardless of fibrous filter types, small (< 100 nm), more spherical in shape aggregates are filtered with higher efficiency than small dendrite-like aggregates.
The results show that morphology of aggregate (size, shape) and fibrous filter structure strongly influence the DEP deposition efficiency, which can lead to difficulties during, for example, theoretical modeling of DEP filtration process.

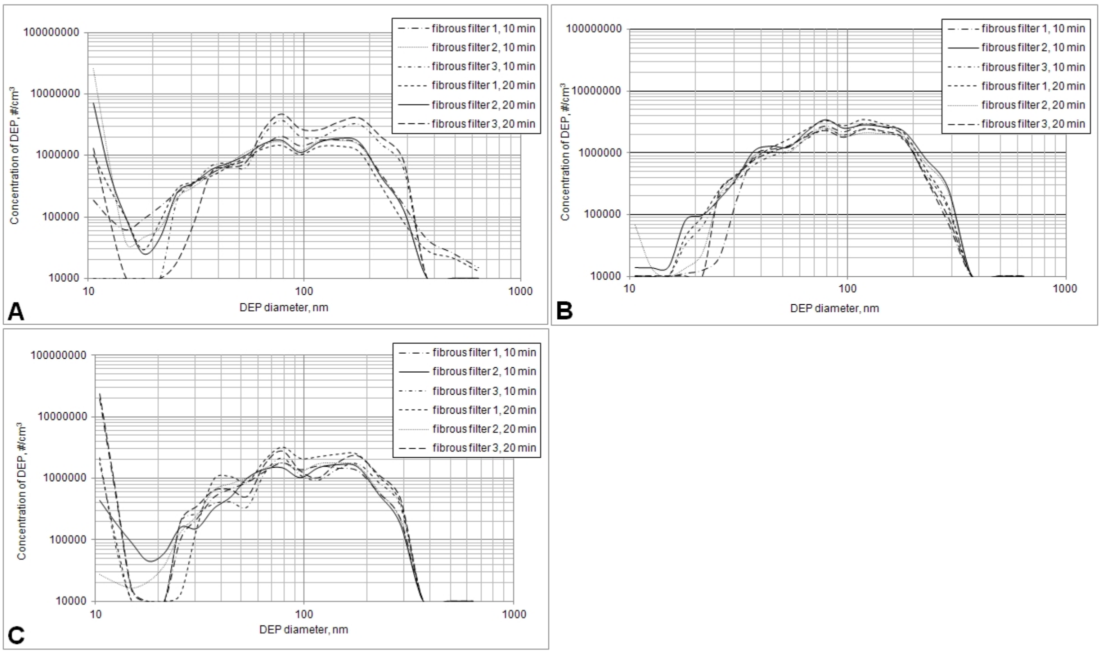

Figure 7: DEP number size distribution in the space beyond fibrous filter A) DEP from fuel I, B) DEP from fuel II, C) DEP from fuel III

Acknowledgments

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