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Application of a Fibrous Electrostatic Filter for Treatment of Diesel Exhaust

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The paper presents results of investigations of a novel method for diesel exhaust filtration in a fibrous filter supplemented by the external electrostatic field (FEF), which may be used to eliminate the occupational hazard near sources of diesel emission. The reported research follows the preliminary basic study of soot removal in such systems (Ciach, Sosnowski, & Podgórski, 1995), and is focused on the construction and testing of a prototype technical-scale FEF device. The results suggest a strong relation between applied voltage and filtration efficiency of the system and demonstrate the influence of aerosol precharging on the efficiency, which can be more than 95%.

diesel exhaust filtration soot particles

1. INTRODUCTION

Diesel engines are widely used in automobiles, generators, heavy-duty vehicles, and railroad locomotives. Air pollution because of exhaust produced by these engines is a serious problem not only in urban or heavy-traffic areas but also in some workplaces. Occupational hazard needs even more attention as it is related to prolonged and high-level exposure to harmful atmosphere. The main groups of occupational risk are mine and tunnel workers (due to closed or poor ventilated volumes), railroad workers, truck drivers, and other people who work near areas where vehicles driven by diesel engines are used or maintained.

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It has been proven that prolonged exposure of rats to diesel aerosols at concentrations exceeding 2 mg/m³ causes a significant increase in pulmonary tumours (Oberdörster & Yu, 1990; Occupational Safety and Health Administration [OSHA], 1996). Because there are some uncertainties about extrapolating animal data to human, both the U.S. Environmental Protection Agency (EPA) and the National Institute for Occupational Safety and Health (NIOSH) recommend a reduction of diesel exhaust exposure to the lowest feasible limit. It should be noted that occupational concentrations range from 0.1 to 2 mg/m³, which is 10–200-fold higher than ambient air levels (Hricko, 1996).

The main health effect of diesel exhaust is related to high concentration of respirable soot, which is considered doubly harmful. These particles overload the lung after deposition (Oberdörster & Yu, 1990) and also carry adsorbed mutagenic substances: polynuclear aromatic hydrocarbons (PAHs). The toxic action of a diesel aerosol is increased when combined with other occupational exposures (e.g., welding fumes, dust, or smoke). Diesel exhaust inhalation at first leads to chronic respiratory symptoms such as persistent cough, bronchitis, reduced lung capacity, or reduced resistance to bacterial infection.

The aforementioned considerations lay at the background of our research on novel effective methods for aerosol filtration. This method might be applied to eliminate soot particles from diesel exhaust. The project focused on various concepts of application of a high-voltage electric field as a factor improving separation efficiency in fibrous filters.

2. GENERATION OF A TEST AEROSOL AND CONCEPTS OF FILTRATION SYSTEMS

Investigation of proposed filtration systems started with a design of a reproducible method for generating a test soot aerosol. Diesel soot consists mainly of submicron particles with a median number diameter approximately 0.1–0.2 microns and it almost does not contain any particles above 0.4–0.5 microns (Kittelson, 1984; Kransenbrink & Georgi, 1989; Patschull & Roth, 1992). A proper test aerosol for diesel exhaust gas filters that base on electric phenomena should show sufficiently high dielectric constant, hence pure soot was chosen (ε = 15). We tested several methods of soot particles generation (Ciach, Sosnowski, & Podgórska, 1995) and we found the ultrasonic generation of liquid suspension of technical soot to be most...
suitable and reliable. Water suspension (1% weight/weight) of commercial soot (STOMIL rubber factory, Poland) was prepared with the use of a minute addition of a detergent. After atomisation in an ultrasonic nebuliser (Figure 1), liquid droplets containing soot were carried with a stream of filtered air to the diffusion drier. In this drier water evaporated leaving dry particles. The soot aerosol that was leaving the drier had satisfactory granulometric distribution (Figure 2) and very stable concentration. The presented method of fine soot aerosol generation is simple and dependable.

![Figure 1. Ultrasonic soot aerosol generator.](image)

The original method proposed for eliminating soot particles from a gas stream was based on aerosol filtration in a layer of a fibrous filter supplemented by an external high voltage electrostatic field (fibrous electrostatic filter [FEF]). During basic studies (Ciach et al., 1995) this filtration system was compared to a classic electrostatic precipitator (EP) and demonstrated better performance at low values of the pressure drop and electric energy consumption.
Another concept under study was related to an application of electrodynamic coagulation (EC) as a method of diesel aerosol pretreatment. Such a process might be useful in aerosol conditioning before filtration to obtain a new size distribution of particles, to decrease the amount of small particles. This process would be suitable for preparing a diesel aerosol for an efficient separation process in such devices as cyclones.

3. DESIGNS AND CONSTRUCTION OF PROTOTYPE DEVICES

The design of a technical-scale FEF prototype was based on our initial studies employing a laboratory-scale model system (Ciach et al., 1995). Those investigations allowed a proper choice of a filtering material, filter structure, and configuration, and finally, a range of voltage applied in the FEF. The prototype electrofilter device is illustrated in Figure 3. The envelope insulated rectangular box of a volume of 5.6 dm$^3$ contained a filtration unit, that is, three steel-plate electrodes and highly porous fibrous material filling. The two outer electrodes were connected to a high voltage DC power supply (TOCHEM, Poland), which provided up to 25 kV.
The inner plate was grounded. The electrostatic field of intensity up to 8.3 kV/cm was perpendicular to the direction of aerosol flow. The space between the electrodes was filled with glass-fibrous material DELBAG (IZOLACJA-MATIZOL, Poland; No. 2 in Figure 3), which was characterised by porosity above 99.8% and good thermal and mechanical resistance. The volume of the filtering section was 3.6 dm³. On the cylindrical inlet to the filter, there was a corona charger (No. 3 in Figure 3), which provided initial aerosol charging. It will be demonstrated later that the charging process had significant influence on the filtration efficiency achieved in the device.

![Figure 3. Fibrous electrofilter.](image)

**Notes.** 1—grounded envelope electrode, 2—fibrous filling of high porosity, 3—corona discharge electrode, 4—high voltage electrode.

The electrodynamic coagulator (EC) designed and manufactured in the project is schematically illustrated in Figure 4. It was constructed as a rectangular insulated box (330 × 25 × 40 mm) equipped with cylindrical input and output lines. Two electrodes made of steel plate were mounted at

![Figure 4. Electrodynamic coagulator.](image)
the top and the bottom of the insulated box. The charging area at the aerosol inlet was equipped with a corona charger connected to a 12 kV DC power supplier, and the agglomeration section was supplied with 10 kV AC voltage (50 Hz).

4. EXPERIMENTAL SETUP

The experimental setup used for investigating the proposed filtration systems is presented in Figure 5. The incoming air is drawn by a fan through the filter not shown in the figure. Before the fan, the air was mixed with soot particles generated by the ultrasonic device. The aerosol (soot concentration of approximately 0.1 g/m³) was blown to the heater and sent to the prototype filter. The aerosol was sampled in two points, a and b, directly after the fan and directly after the filter, respectively. Analyses were conducted with two devices connected in parallel: a laser analyser LAS-X (Particle Measuring System, USA) and a condensation nuclei counter Portacount (TSI, USA). This configuration of analysers allowed determining both total aerosol penetration through the filter and size distribution of the aerosol. The electrodynamic coagulator was tested in a similar configuration but without the heater.

Figure 5. Experimental setup. Notes. 1—fan, 2—ultrasonic atomiser, 3—heater, 4—prototype filter, a and b—sample ports.
5. RESULTS

The research focused on analysing the filtering prototype performance. The influence of the chosen process parameters, that is, voltage applied to the filter and to the charger, aerosol temperature, and its residence time in the filter were investigated. Efficiency of the FEF is defined here as

\[ \eta = \frac{n_{\text{in}} - n_{\text{out}}}{n_{\text{in}}}. \]  

As the number of penetrating particles seems to be an important factor for health hazard, the efficiency of the prototype filter was also compared to the efficiency of the same device without the fibrous layer, which acted in that way as a common electrostatic precipitator.

It is clear that the presence of a highly porous fibrous bed increases filtration efficiency. Fibres made of a material of a high dielectric constant strongly disturb the external electric field in its proximity. Fibres become bipolar charged because of induction and attract particles. In addition, also particles act as a dipole in an external electric field.

5.1. Influence of Electrode Voltage and Aerosol Temperature

Filtration efficiency for two values of operating temperature, 20 and 90 °C, as a function of voltage applied to the filter electrodes without precharging of the aerosol is presented in Figure 6. Aerosol flow rate through the filter was \( Q = 300 \text{lpm} \), thus aerosol residence time in the filtration section was \( \tau = 0.72 \text{s} \). Pressure drop across the filtering device in the aforementioned conditions was about 300 Pa. It can be seen that good separation required very high voltage (above 20 kV) applied to the electrodes of the FEF. It is also demonstrated that temperature had no appreciable influence on filtration efficiency.

5.2. Influence of Aerosol Residence Time (Flow Rate Through the FEF)

One of the most important operation parameters in the system should be the residence time of the aerosol in the filtration unit. Figure 7 is an illustration of the relation between efficiency achieved at the filter and voltage for two
values of aerosol flow rates, 300 and 600 lpm, which correspond to two values of residence time in the filtration section, 0.72 and 0.36 s, respectively.
Longer residence time allows more efficient removal of soot particles from a gas stream. On the other hand, the twice-higher flow rate through the FEF unit decreases efficiency by no more than 5%. This feature of the system offers an opportunity to easily control the emission through the filter in respect to the fluctuating load (aerosol flow rate) by small changes in voltage.

5.3. Influence of Aerosol Precharging

It was mentioned before that precharging of the aerosol was supposed to have a significant influence on total filtration efficiency. This relation is shown in Figure 8. Measurements were done for residence time 0.72 s at room temperature. Voltage applied to the corona charger and to the FEF electrodes was identical (from the same power supplier) and it was limited to the highest value of 15 kV (corona current: 0.25 mA) because of spark generation.

![Figure 8. Filtration efficiency as a function of corona charger voltage. Notes. B—with corona precharging, A—without corona precharging.](image)

Corona charging of the aerosol dramatically enhanced the separation effect: The same values of efficiency could be obtained at electrode voltage values about 10 kV lower than in the system without charging.
5.4. Comparison to Electrostatic Precipitator (EP)

Figure 9 presents filtration efficiency versus voltage relationship at two flow rates, measured in the proposed device after removal of the fibrous bed. In that case unit operation was similar to the performance of an electrostatic precipitator (EP). Compared to the efficiency of the FEF (Figure 9), the values obtained for the EP (at the same pressure drop) were significantly lower, especially for shorter residence time. This result demonstrates how different filtration mechanisms are when fibres are present between electrodes generating an electrostatic field. This effect exists mainly due to dielectroforetic interactions that are present in the non-uniform electrostatic field being a result of fibres polarisation.

![Figure 9. Filtration efficiency of a fibrous electrostatic filter (FEF) prototype without fibrous filling.](image)

5.5. Application of an Electrodynamic Coagulator (EC)

As it was demonstrated earlier, even the use of high voltage and precharging of the aerosol had not limited the penetration through the FEF below 5%. This result is mainly due to poor filtration of particles of approximately 0.1 μm (Ciach et al., 1995), for which there is a minimum of all filtration mechanisms.
Investigating methods intensifying the deposition of this fraction in the FEF device, we proposed pretreatment of the aerosol in an electrodynamic coagulator (EC). Electrodynamic coagulation is based on the following principle: During field charging of the aerosol, particles collect an altered number of elementary charges. Because of their different diameters, particles show various electrical mobility. In an external alternated electric field, they oscillate with different amplitude. These oscillations increase the number of collisions and promote agglomeration of particles.

The effect of electroagglomeration of the soot aerosol is illustrated in Figure 10. It can be seen that even for a very long residence time, $\tau = 3$ s, only a small shift in distribution can be observed.

![Figure 10. Influence of electrodynamic coagulation on soot particles' number distribution.](image)

We do not find this method applicable for the intended purpose. The shift of the number distribution curve towards higher diameters of particles is small and leaves the amount of undesired particles (about 0.1 $\mu$m) almost unchanged.

There is, however, a problem that should be addressed for future research: the influence of higher aerosol temperature and concentration on the process. On the basis of theoretical background one may expect better performance of the EC at very high aerosol concentration and elevated temperature.
Unfortunately, these conditions were not investigated within the current study.

5.6. Testing of the FEF Prototype in Real Conditions

The results of our research encouraged us to attempt to operate the FEF prototype at the outlet of a real automotive diesel Talbot engine (1800 ccm). We found problems in the operation of the system during the warming-up of the engine due to high humid condensation in the filtration unit. Therefore, the electric equipment could not be used in those conditions. It may be expected that also other technical problems will appear when an FEF system is used in a moving vehicle or a car (mechanical vibrations, fluctuations of load, etc.). Application of the device in a mobile vehicle seems to be impossible at this stage of the project. It needs more research on the special technical arrangements that allow this effective method of filtration to be used in such unfavourable operating conditions.

6. CONCLUSIONS

In this work, we have presented results of research on some methods of treating the aerosol emitted by diesel engines. Application of a high-voltage electrostatic field during aerosol filtration in a fibrous material was demonstrated to be a highly efficient method of separating soot particles, especially when aerosol precharging is used. Additionally, the proposed prototype technical-scale FEF device was characterised by a low pressure drop. The application of the designed filtration system was limited to gases that are not too humid, as water condensation makes the operation of the electrical section impossible. At this stage of the project, it was not possible to propose this method for cleaning the exhaust directly in a down-stream process in mobile vehicles or cars. However, there is another possibility of using the FEF, especially in workplaces highly polluted by diesel emission: in the form of a stationary air-cleaning device. In some locations, where air exchange is limited (tunnels, garages, mines), this method may be an economic way of efficiently removing soot particles from gaseous atmosphere. In this case, the working environment may be protected against a high concentration of a harmful diesel aerosol.

The influence of deposited carbon in the fibrous structure remains an unresolved problem left for future investigation. Only a 5-hr exposition was
performed and we did not find any change in filter efficiency. Probably, like in a standard exhaust system, after collecting a high amount of soot, the filtering system should be burned out.

REFERENCES


