Nanofiber Media Performance in Application to Motor Vehicle Air Filtration

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Abstract

The function of air filtration systems in motor vehicles is to improve air quality and cleanliness in car interior, control the respirable particle concentration in the operator's cabin, and reduce the dust concentration in the engine intake air to an acceptable level.

In these applications, limited space is available for the air filtration systems. Therefore, filters are designed in smaller packages, resulting in higher aerosol velocities through the filters. Such high aerosol velocities may cause dust reentrainment leading to an increase in the amount of dust penetrating the filter. Moreover, motor vehicle environments are extremely varied and these environmental and operational conditions influence filter performance.

Cabin filtration systems are used to improve air quality and cleanliness in the car interior, or operator cabin and to protect air-conditioning system components from dust. Although car interior air filtration utilizes several advanced filter design technologies, these systems are still being improved because of the relatively low efficiency of current filter media caused mainly by high air velocity due to space limitation and very low permissible pressure drop. In contrast, high efficiency filters are required for operator cabins since these filters have to protect operators from high concentrations of small 0.01 – 10 micron particles such as silica, coal and others harmful contaminants.

The main function of an engine air induction system is to remove contaminants from the incoming air stream that can cause engine wear leading to performance loss, increased exhaust emissions, increased operation and maintenance costs or catastrophic failure.

Engines consume large amounts of air, since approximately 12 m^3 of air is needed to burn 1 liter of fuel. This massive airflow rate requires filter media with high permeability in these applications.

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Typically, motor vehicle filters must meet the following general specifications: low flow restriction; high dust-holding capacity; highly efficient air cleaners (initial and total efficiency); small, compact components; long life; exclusive designs.

Nanofiber media utilization helps to develop smaller, more compact components and long life filters that have higher initial efficiency, and low initial pressure drop. The increased efficiency gained by using nanofiber media does not cause the usual consequent pressure drop penalty. Moreover, properly designed nanofiber filter media have lower reentrainment of already collected particles. In addition, because of the lower restriction, engine fuel consumption will decrease.

The basic understanding of filtration mechanisms are not well known on the nano scale and only limited literature is available. The behavior of nanofibers in the filtration of airborne contaminants is starting to be quantified. Classical fluid dynamic mathematical models used in the continuum region of the filtration process do not apply to the slip flow that takes place around nanofibers. As a result, experiments are still the main information source regarding the filter performance characteristics.

This paper focuses on media performance requirements in motor vehicle air filtration applications, discusses the filtration process in nanofiber media, and provides filter performance characteristics for media and filters.

Keywords

Motor vehicle air filtration, cabin filtration, engine air filtration, filtration process in fibrous filter media, filter environments, nanofiber media performance, filter efficiency, dust holding capacity, reentrainment.

Needs for Nanofiber Filter Media in Motor Vehicle Air Filtration

It is required that any engine air filter should achieve maximum dust holding capacity, Δm; thus maximum life in service, while obeying two other requirements:

$$E \geq E_{min} \text{ and } \Delta p \leq \Delta p_t$$

Where E_{min} is the minimum specified efficiency, Δp is pressure drop, Δp_t is the terminal, or maximum acceptable pressure drop.

Cellulose-type filter media, dual-layer cellulose-meltblown, synthetic nonwovens, charged are often used in motor vehicle air filtration. These media are made of relatively large fibers with fiber diameters usually larger than approximately 20 microns. Only meltblown fibers are smaller, mostly in the range of 2-10 microns. Filter efficiency is not high for small dust particles encountered in on-highway environments because of the relatively large fiber diameter. High efficiency is achieved by increasing media solidity and lowering aerosol velocity. This approach also prevents reentrainment. The random spatial arrangement of fibers in nonwoven synthetic filter media and cellulose papers results in a wide pore size distribution. Large pores, offering paths of low restriction to aerosol flow, act as the source of pinholes. As other regions of the filter become increasingly restricted by dust accumulation, the velocity increases through these pores, resulting in penetration of both uncollected and reentrained particles. This process is intense at high aerosol velocities. Moreover, filter efficiency is relatively low until dust cake is formed on the filter media [Jaroszczyk, et al, 1993, 1999]. This is the worst time for engine wear because a large amount of dust reaches the combustion chamber at the beginning of filter operation. Using nanofiber media diminishes this increased particle penetration.

Pressure drop is usually the most important factor in the set of filter design assumptions. It is directly linked with aerosol velocity that can range over an order of magnitude during operation. In the case of engine filtration with flow rate of approximately 5 to 5000 m^3/h, the media velocity is in the range of approximately 1.5 to 200 cm/s. The high end of this range represents prefilters, while the range of 1.5 - 25 cm/s is common for pleated engine main filter elements. The highest velocity in car cabin filters can reach the level of 30-50 cm/s at the high blower speed.

Pressure drop significantly increases with decreasing fiber diameter since it is a function of $1/d_f^2$ in the continuum flow region in which classical motor vehicle filter media operate. In the slip flow regime described by large Knudsen numbers ($Kn \geq 0.3$ corresponding to $d_f \leq 400$ nm), the pressure drop is lower, reaching it lowest level in the free molecule regime (Knudsen number is greater than 10 - this corresponds to fiber diameters (d_f) smaller than the free molecule path, which is approx. 65 nm) where it is a function of $1/d_f$, [Pich, 1969, 1971, 1987; Cheng et al, 1988]. In general, the larger the Knudsen number, the lower the pressure drop. However, this is a valid case only for relatively clean filters. When dust deposits form on nanofibers, this benefit of low-pressure drop diminishes with increasing amounts of deposited dust. Moreover, nanofibers capture very fine particles. The pressure drop increases more rapidly for this compacted dust cake. Therefore, it is important to design nanofiber filter media with significantly higher permeability than classical cellulose media to obtain long life filters.

Efficiency increases rapidly with decreasing fiber diameter. For instance, using 1 μm instead of 50 μm fibers leads to an increase in filter efficiency by a factor of 2000 [Pich, 1987]. The efficiency increases drastically when nanofibers are utilized. The ratio of nanofiber diameter to cellulose fiber diameter is approximately equal to 1:130. This results in an enormous surface area increase for nanofiber filter media. Surface area for 200 nm nanofibers is approx. 20 m^2/g while only 0.2 m^2/g for 20 -micron cellulose or spunbond fibers. In the case of the nanofiber media, particles are attached to nanofibers that cover the large pores formed by cellulose fibers. Therefore, they cannot penetrate the filter. In contrast, the pores stay open in the cellulose media; thus small particles can penetrate the media and reach the engine combustion chamber. Figure 1 shows collected dust particles by cellulose and nanofiber filter media. Because the aerodynamic drag force on nanofibers is low compared to the drag on the large dust particles collected on the nanofiber media, this media are ideal for application to self-cleaning filtration. The particles can be easily detached by applying reverse airflow or just shaking the filter. The second type of cleaning is very important in mining applications where filter life in measured in days due to high dust concentrations. While not all products are designed to allow filter cleaning, this performance improvement demonstrates potential future benefit regarding cleanability.

Figure 2 shows self-cleaning performance for cellulose and nanofiber filter media. The cellulose media developed a residual internal dust cake that cannot be efficiently removed during pulse cleaning, resulting in a significant pressure drop increase. In contrast, the pressure drop increase in nanofiber media is slow allowing hundreds of cleanings.

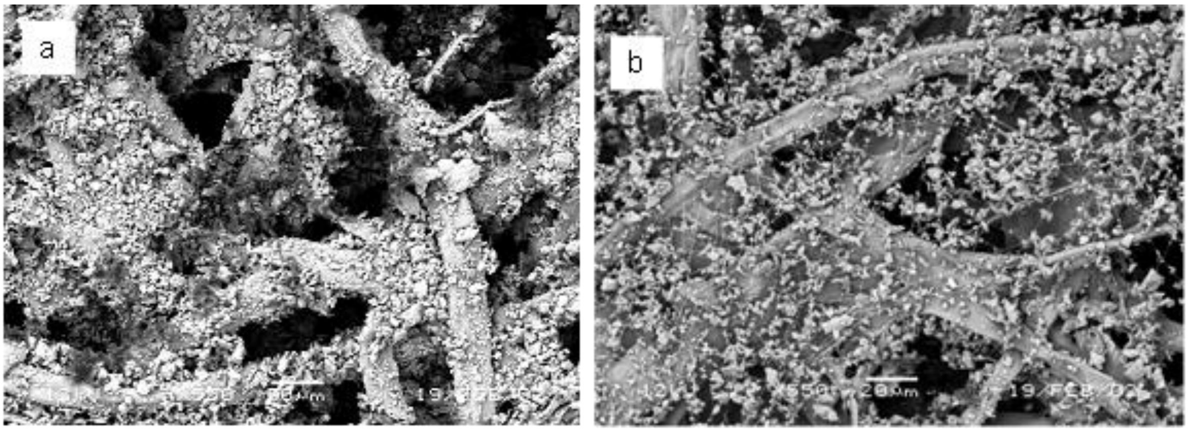

Figure 1. Dust particle deposit on cellulose fibers (a) and nanofiber filter media (b).

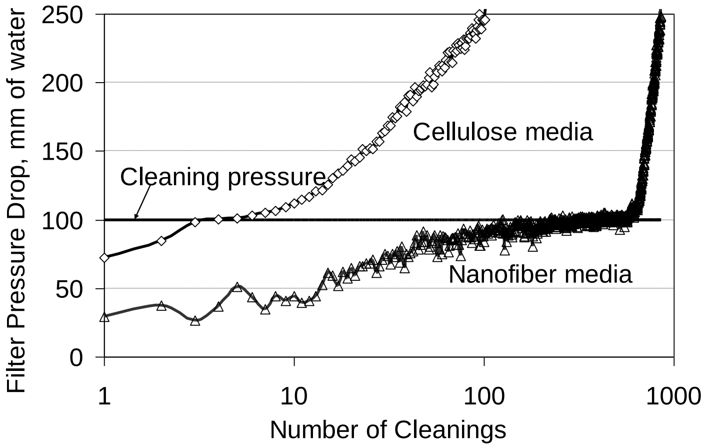

Figure 2. Pressure drop during dust loading for cellulose and nanofiber filter media.

Performance of New Nanofiber Filter media.

During the development of nanofiber filter media for motor vehicle air filtration, the following questions were asked:

- What is the relative importance of each basic filtration mechanism in nanofiber media?
- How to describe the interaction between large particles and nanofibers?
- How to describe the interaction between fine particles and nanofibers?
- How to study the interaction between the nanofiber layer and the substrate?
- How to describe the role of the electrostatic mechanism for nanofibers?
- How to determine the minimum mechanical strength of the nanofibers at which the dust deposit does not destroy the nanolayer?
- Are nanofibers strong enough to last in filtration applications of heavy particles at high velocities and high differential pressure?

- How to estimate the cleaning efficiency for nanofiber self-cleaning filters when compared to other media?
- How to measure/simulate adhesion of layers of nanofibers to the substrate?
- Is the adhesion adequate to process the nanofiber media on high-speed pleaters?

Cellulose and synthetic substrates were considered during the development process. Nanofibers with basis weight less than 0.1 g/m^2 with a diameter of less than 400 nanometers were applied to the substrate. Uniformity of nanofibers (Figure 3) was achieved which resulted in obtaining high media permeability (21 cm/s), approximately 2.5 times greater than the typical media used for commercial HD media applications (trucks, construction equipment, etc.). The highly permeable media provide higher efficiency than commercial nanofiber filter media – Figure 3.

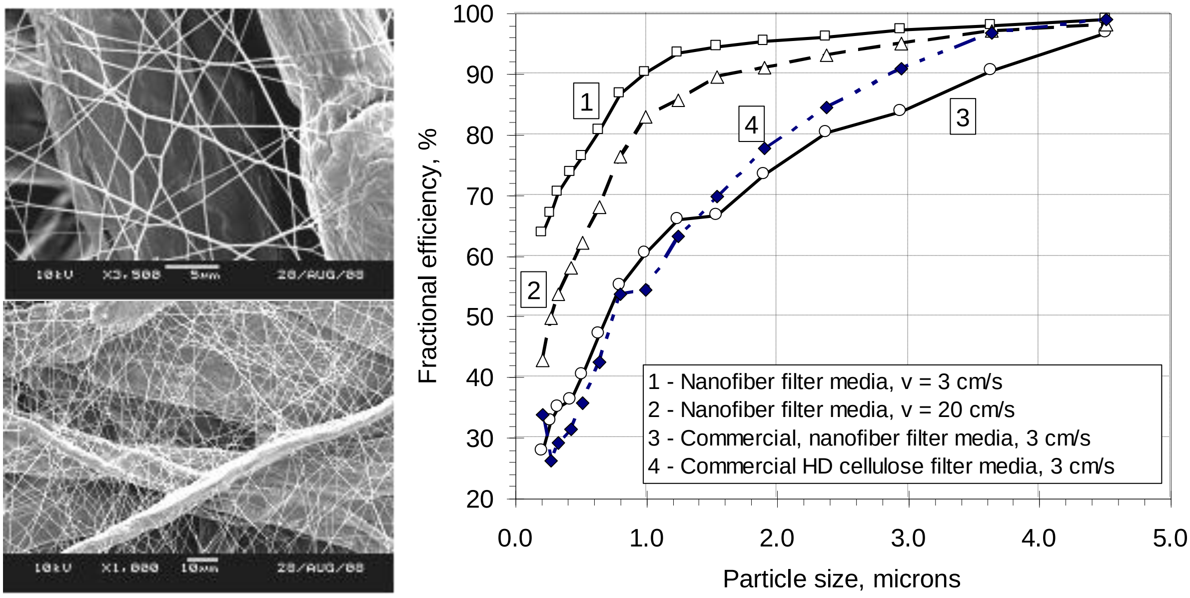

Figure 3. Nanofiber distribution (lower and higher magnification) and media fractional efficiency.

Conclusions:

- Nanofiber offers high initial efficiency for small particles and fractional efficiency drastically increases when nanofibers are applied to a substrate. There is a direct correlation between filter performance and the amount of applied nanofiber. Initial pressure drop of nanofiber media is low, with high airflow permeability.
- Nanotechnology helps to develop smaller, more compact components/long life filters that have higher efficiency, and low initial pressure drop. The “positive” dust shedding - self-cleaning characteristic makes the nanofiber filters suitable for dusty environments where several cleanings are specified.

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