RECENT DEVELOPMENT IN HEAVY DUTY ENGINE AIR FILTRATION AND THE ROLE OF NANOFIBER FILTER MEDIA.

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Abstract

The development of an engine air filter is based on filter performance requirements, vehicle's operational environment, available space, filter media properties, and production technology. The design process includes analyses of theoretical and empirical models describing filter media performance and aerosol flow in filter housings and through filter elements. Filter media are carefully selected based upon these models and simplified laboratory tests. The filter element design is evaluated in great detail through a series of laboratory and field experiments.

The role of the engine air induction system has increased because of recent engine exhaust particulate and evaporative emission regulations. Engine lifetime, engine emission and fuel consumption depend on the air induction system design and its performance. Providing optimized solutions for these requirements dictates filter development trends. This drives the need for smaller, more compact filters and more efficient filter media with higher permeability. The efficiency can be drastically improved by applying a layer of nanofibers to a cellulose or synthetic substrate. The ISO fractional efficiency test method, that in its final stage of development, can clearly show the advantage of nanofiber filter media. This paper discusses air cleaner design including the newest in-line reduced volume air cleaners and the role of nanofiber filter media in engine air filtration.

Keywords: *engine air induction system, filtration process modeling, filtration mechanisms, filter development process, nanofiber filter media, air filter performance, filter efficiency, dust holding capacity, reentrainment, testing.*

1. Introduction

Major progress in engine air filtration in recent years has been made by introducing in-line; flow-through fluted and pleated filters, and nanofiber filter media. The fluted and

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pleated in-line, reduced-volume filters, provide high filtration performance while occupying less space. In these designs, almost the entire volume of the filter housing accommodates the filter media. The nanofiber filter media offers high efficiency and high permeability. In other words, the efficiency of nanofiber filter media is high at lower flow restriction when compared with traditional cellulose filter media.

Traditional surface type cellulose and surface type synthetic filter media that predominate the engine air filtration market can deliver high dust capacity and high gravimetric efficiency when a dust cake is formed on the media, which takes some time. The initial efficiency and fractional efficiency for fine dust particles of traditional filter media is too low in many applications. Despite this fact, the most commonly used media is still resin-impregnated cellulose paper, because it has low cost and has the ability to pleat into a densely packed pleat block with well-defined pleat shape. However, recent achievements in nanofiber media technology minimize the cost of the media. Knowing that less nanofiber media is needed to construct a filter because of the high media permeability, the nominal cost of the nanofiber media will not increase the overall cost of the filtration system. In fact, the cost may be even lower since smaller filtration systems can be designed for a given flow rate.

The engine air filter market is driven by the following performance requirements for engine air induction systems: low flow restriction, high dust-holding capacity (long life or service-free designs is the main objective in many applications), high gravimetric and fractional efficiency, small, compact components, integrated air intake & silencing system, permanent air intake systems with zero evaporative emissions, exclusive designs, volumetrically efficient filters to fit into available space.

The importance of the engine air induction system has recently increased because of governmental engine exhaust particulate and evaporative emission regulations. Contaminants from the air intake system may significantly contribute to the total engine emissions including crankcase emissions in case of low efficiency filters. According to Schilling [Schilling, 1972], 30% of contaminants penetrating the air induction system and entering the engine passes out the exhaust. In order to reduce the contaminant concentration downstream of the filter, highly efficient filters are needed. High efficiency can be achieved by utilizing nanofiber filter media and proper air intake system design.

Engine operation, lifetime, engine emissions, and fuel consumption depend on the air induction system design and its performance. By integrating the intake and exhaust systems in the new Cummins QSL9, the engine meets EU Stage IIIB and EPA Tier 4 Interim off-highway emission regulations. Moreover, the new system design that was introduced in April 2009, results in efficient combustion that leads to a reduction in fuel consumption by up to 5 percent, dependent on rating [Diesel Progress on Line, August 2009]. The reduced volume Direct Flow filters are 35% smaller then the standard air cleaners.

The objective of this paper is to review the newest engine air induction systems. The focus will be primarily on the design of recently introduced air cleaners and filter media design parameters, their performance and the development trends. In contrast to filters used in industrial applications, ventilation systems, and clean room technology, motor vehicle air filters operate at variable flow rates and flow pulsation experienced frequently in city driving and under variable environmental conditions. The filters are variably loaded with polydisperse dusts at changeable aerosol velocities. The velocity changes can range over an order of magnitude during operation with flow rate of 5 to 5000 m^3/h. The flow rate can be even higher in case of equipment used in the mining industry. The media velocity is in the range of approximately 1 to 200 cm/s. The high end of this range represents prefilters while the range of 0.5 - 25 cm/s is common for pleated main filter elements.

Panel and cylindrical air cleaners still dominate the market. These designs require large housing volumes with relatively small inlets and outlets. Flow turbulences that usually develop in the transition, sudden contraction or sudden expansion areas (Figure 1a), are sources of increased pressure drop. Losses due to turbulent motion of the air increase significantly with increased velocity, because the inertial force is proportional to the velocity squared: $\Delta p = \zeta \bullet \frac{\rho \bullet v^2}{2}$; where ζ = pressure loss coefficient, ρ = air density, v = air velocity. The ζ coefficient is the main contributor to the total pressure drop in a housing with a sudden contraction and sudden expansion [Fried and Idelchik, 1989].

Turbulence can be reduced by minimizing these transition spaces. One method is to incorporate media into the empty spaces. This method was used in the reduced volume filters that will be discussed later. Experiments have shown [Jaroszczyk, T. at al, 2004] that at a nominal engine flow rate, the pressure drop of a panel filter housing can exceed the pressure drop of a clean panel-type filter element by a factor of three.

Figure 1 shows flow pattern in the traditional panel air induction system and in a Direct Flow air cleaner. The pressure drop in a panel filter drastically increases in the transitions between the inlet and the housing and the housing and the outlet. The smooth transition in the Direct Flow and other in-line filters minimizes flow restriction.

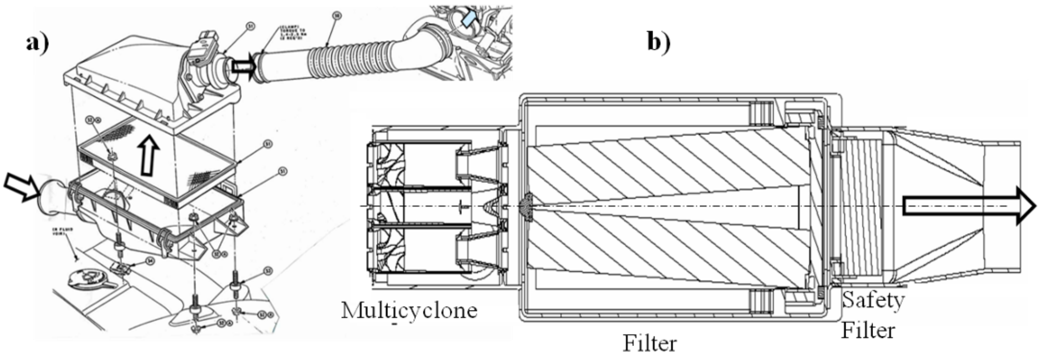

Figure 1. Schematic view of a Panel Filter- a) Direct Flow filter- b)

2. In-line (Axial Flow) or Reduced Volume Filters

A historical view of automotive air filters was probably first published by Clarke Rodman [Rodman, 1998]. The development of panel and cylindrical filter elements, and filter media is discussed. Here, we will focus on the recently introduced in-line or reduced volume filters constructed of flutes or pleated media blocks.

In-line or reduced volume filters, those having a high media utilization coefficient, are a relatively new family of engine air filters gradually reaching the engine air filtration market. These filters have been designed to meet the requirements for small packaging while at the same time maintaining or exceeding high performance. The axial flow pattern avoids turbulences by allowing the aerosol to flow straight through the filter. It leads to the decrease of potential pressure losses.

The Donaldson PowerCore filtration technology [Donaldson Brochure, 2002, DIESEL PROGRESS North American Edition, 2008, Donaldson Presentation, July 2009, Adamek, 2008] that combines axial-flow filer design with Ultra-Web® nanofiber filter media technology is the most known design. It has been employed mainly in the following applications: truck, construction equipment, agriculture, and power generation. On-highway applications still remain the major application of the PowerCore fluted filters with nanofiber filter media. More than 5 million filters have been sold. Donaldson PowerCore filter technology has 27 patented features.

The PicoFlex® filter utilizing triangle flutes [Mann+Hummel PicoFlex® Brochure, 2004, Peltz et al, 2003] is the second fluted design that has reached the engine air filter market. The CompacPlus® filter element (Figure 2d) has 50% more filter media surface area than the conventional filter element. Currently, Mann + Hummel offers the IQORON air cleaner series made of pleated media blocks (Figure 3). The air cleaned may be equipped with high efficiency multi-cyclone block precleaner that is a standard or optional separation stage used in many in-line air cleaners.

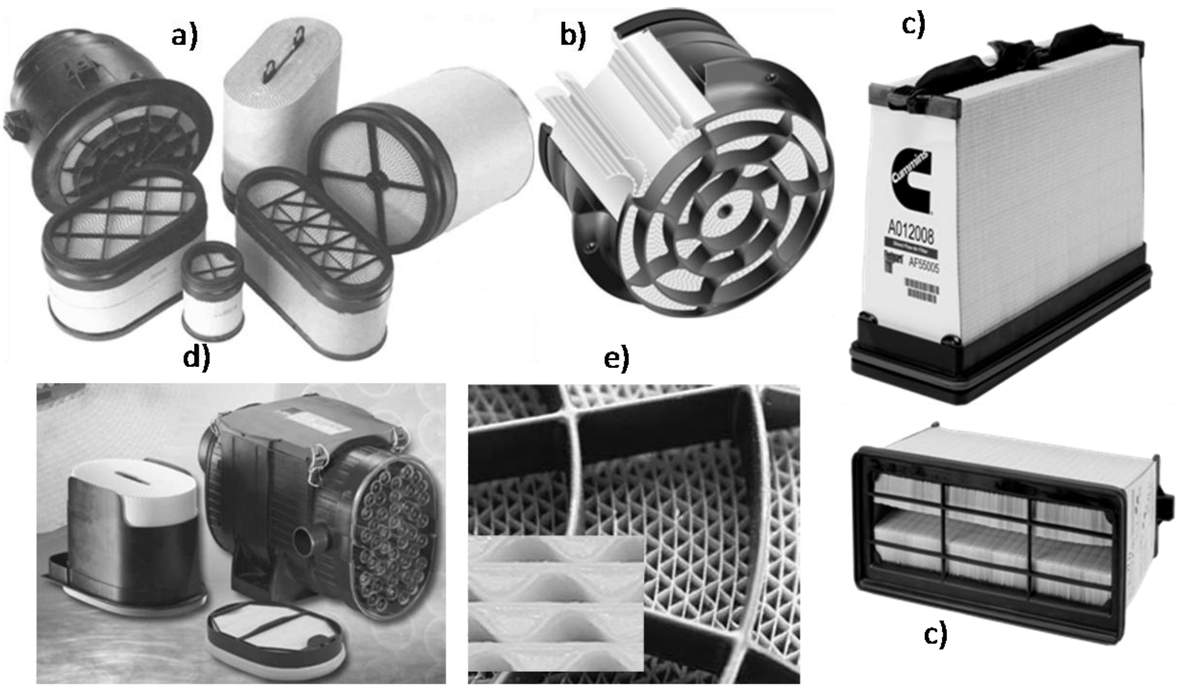

Figure 2. In-line fluted and pleated air filters: a)-Traditional PowerCore - (Donaldson), b) - Channel Flow (Baldwin), c) Direct Flow – Cummins, d) - PicoFlex - (Mann+Hummel, e) – block of flutes

The third successful fluted design was introduced by Baldwin [Baldwin brochure - form 346] as the Channel Flow® Air Filters. According to Baldwin, the design allows a reduction of the amount of space by up to 50% when compared to traditional filters. Examples of all known in-line fluted air filters are shown in Figure 2.

The fluted design shown in Figure 2 can have an oval or triangle shape. The design and flow pattern are discussed in details elsewhere [US Pat. Des. 396,098, US Pat. Des.

437,402]. The fluted design has been known for decades, [US Patent 2,210,397, 1940; US Patent 2,259,092,1952, US Patent 3,025,964, 1962; US Patent 4,430,223, 1984] to mention a few. These filters are discussed in detail by Pratt [Pratt, 1985]. However, Donaldson was the first company that successfully delivered this solution to the market reaching both the original equipment and aftermarket applications. The success was possible by combining the optimized design, advanced nanofiber media technology and efficient production technology. Determined support of these three areas led to the development of Donaldson PowerCore™ G2 filters with 30 percent smaller footprint with the same straight-through airflow and high-density filtration system as the "original" PowerCore and 50% size reduction when compared to the traditional cylindrical filters. This technology was introduced at the 2008 ConExpo-Con/Agg Show in Las Vegas in March. Examples of PowerCore™ G2 filters are shown in Figure 3. The filters can have cylindrical, oval, and rectangular shapes.

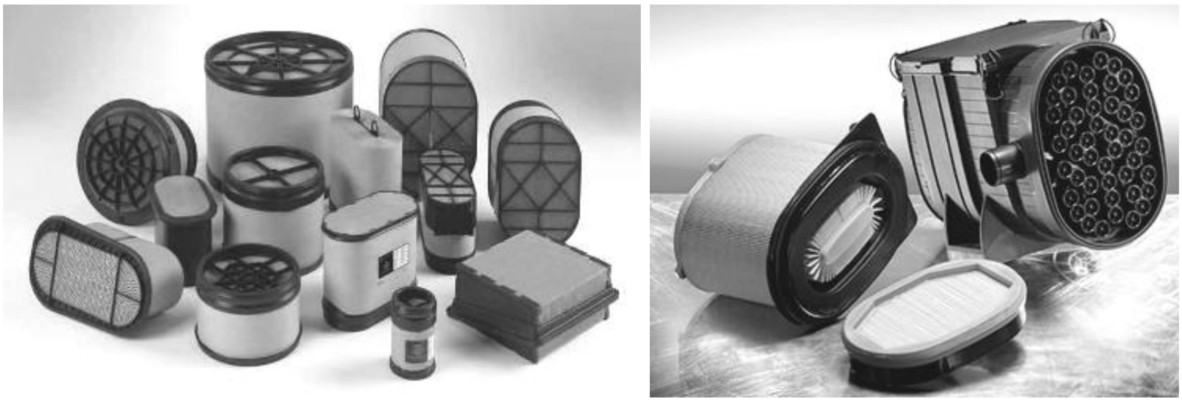

Figure 3. Donaldson PowerCore™ *G2 filters on the left and Mann+Hummel IQORON designs*

Although straight-though flow filters have been known for a long time [US Patent 4,157,902, 1979], the conical design [US Patent 5,106,397, 1991, US Patent Design 342,900, 1991] that was introduced by Ford in the 1990's was one of the first designs that reached the market. The filter fully utilizes the low resistance coefficient of the bullet shaped insert and the flow-straining feature of open pleats at the filter element inlet. The bulleted inlet is not used in the Mann + Hummel IQORON design with similar approach to the main filter design. For an almost identical media surface area, the pressure drop of the conical filter element is only 46% of the panel filter element. Pressure drop for the conical air cleaner, including housing and the filter element, is 39% lower than its panel filter counterpart [Jaroszczyk, et al, 2004].

In contrast to the fluted designs, the Cummins Direct Flow axial filters that were first patented in 2002, utilize alternating sealing technology [US Patent 6,375,700, U.S. Patent 6,482,247, U.S. Patent 6,511, 599, US Patent 7,314,558, US Patent 7,323,106, U.S. Patent 7,097,694]. The majority of the Direct Flow design incorporates equalized contaminant passages in the form of spaces between individual pleated elements, which prevents such clogging (Figure 2c). The pleating technology used in the construction of Direct Flow filters enables the use of high-speed rotary pleaters. Such elements can be added to obtain a larger filter as flow rate increases, filtration performance specifications change (increases in dust capacity or efficiency) or dust concentration increases. The individual pleated filter elements are sealed with a leak-free bond on one end and open on the opposite end. This type of design prevents contaminant from leaking without being filtered to the required level of particle size and concentration. Figure 4 shows Donaldson Power Core air induction system and Cummins Direct Flow air cleaners. The Figure shows that the dust cake is uniformly distributed on the entire length of the flute. This is a positive feature since uniform dust cake contributes to greater dust holding capacity of the filter.

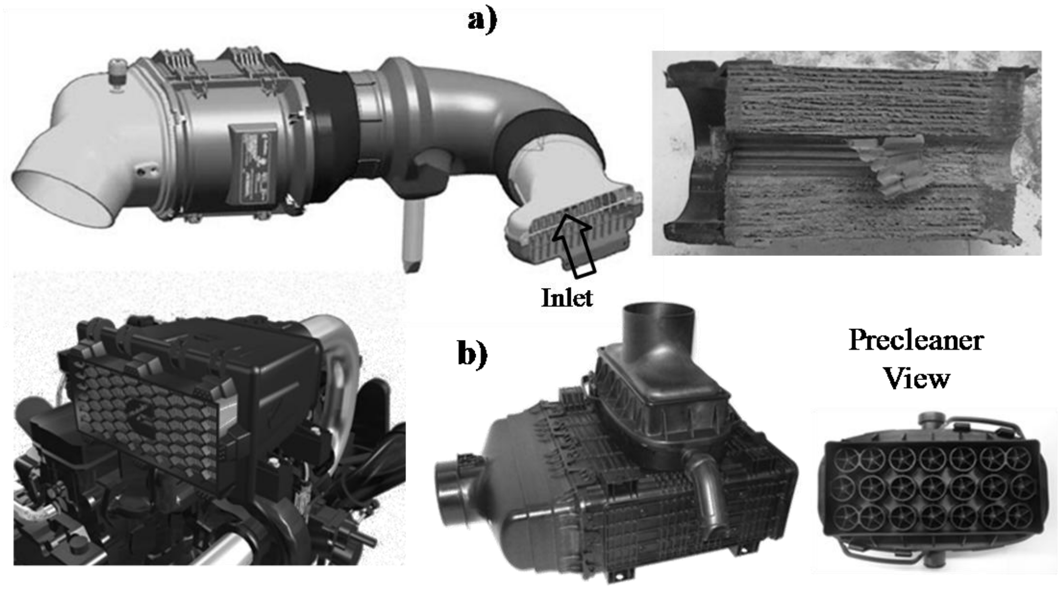

Figure 4. a) - Donaldson's Power Core air induction system on the left and dust cake in the filter, b) - Cummins Direct Flow air cleaners, left – on an engine, center – assembly

The frictional forces, flow around pleats or flute edges, and the flow across the filter media are the main factors responsible for flow restriction. The optimum flute length is typically between 150 - 300 mm. The length of the pleated in-line filters can be greater.

Because of the relatively small volume of the in-line air cleaners, they can be incorporated with a large engine (Figure 4) under the hood, or just behind the truck cabin.

3. The Role of Nanofibers in Engine Air Filtration

Dust cake filtration dominates in an engine's main filters, which are commonly made of cellulose or synthetic pleated thin filter media. When dust particles deposit inside the media, the porosity decreases and the effective fiber diameter increases. As a result, filter efficiency increases and pressure drop increases (for fine dusts, drastically) because decreased porosity causes increased air velocity inside the partially clogged media. At the same time, the efficiency decreases because of increased fiber diameter. To avoid drastic pressure drop increase, particles, especially the fine "clogging" type, should be kept on the media surface. This can be done by applying nanofiber to the media influent side. Moreover, when the particles accumulate as a dust cake on the nanofiber media surface, they can be easily removed by shaking, or reverse flow, or even filter vibration during motor vehicle operation. Pressure drop in cellulose media can be described by an equation [Myedvyedyev et al. 1984] $\Delta p = \dfrac{\mu \cdot v \cdot m \cdot h}{d_f^2 \cdot \rho_f \left(-0.984 \ln \beta - 0.47\right)}$, where μ = air dynamic viscosity, m = media basis weight, h = media thickness, ρ_f = fiber density, ß = filter solidity (or packing density) - volume of fibers/volume of filter. Pressure drop here is a function of $1/d_f^2$ (d_f = fiber diameter) and is a linear function of media thickness h and a complex function of packing density. Pressure drop in the free molecule and slip regions is a function of $1/d_f$ [Pich, 1969, 1971; Cheng et al, 1988] that occurs when fiber diameter is below approximately 400 nanometers under standard flow conditions. Therefore, nanofibers are essential to achieving a high efficiency of particle removal at relatively low-pressure drops as it described by an equation $\Delta p = 2.29 \frac{\mu \cdot v \cdot m \cdot h}{r_f \cdot \lambda}$, where r_f is fiber radius [Pich, 1969].

Because of the dependency of the efficiency and pressure drop on fiber size and because of slip flow at the fiber surface, nanofibers become highly desirable for filtration applications [Kosmider and Scott, 2002]. In other words, when fiber diameter decreases to nanometers, the gas flow is in the molecular (or transition) regime and the pressure drop decreases. However, this is valid only for clean filters. When dust deposits are formed on nanofibers, this benefit of low-pressure drop reduces with increased amount of the dust deposit. On the other hand, the permeability of nanofiber filter media is approximately 2.5 greater than the typical media used for commercial HD media applications (trucks, construction equipment, etc.). In other words, the pressure drop increase starts from 2.5 times lower initial pressure drop than the standard media. Therefore, the clogging process is longer. This is important especially for ultrafine particles since dust cake of fine particles has low permeability.

When the particles are uniformly distributed due to a huge surface area of the nanofiber layer, this cake causes less flow restriction. The specific surface area in the case of nanofibers is approximately 250,000 times greater than cellulose media. In the case of the nanofiber media, particles are attached to nanofibers that cover the pores. 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. Dust particle distribution on cellulose and nanofiber filter media is shown in Figure 5.

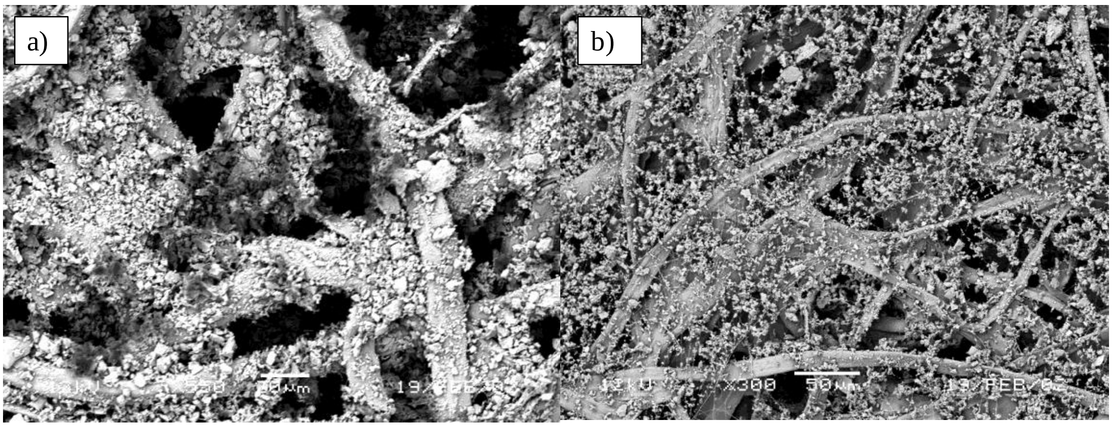

Figure 5. Dust particle distribution on cellulose filter media – a) and on nanofiber filter media – b)

Nanofiber filter media are not new in the filtration industry. In fact, the media reached specialized markets such as high efficiency filters for military ventilation, both mobile and stationary applications, and high efficiency face masks, more than 50 years ago [Filatov, 1997; Stokozov, 2002; Filatov, Budyka, and Kiriczenko, 2007]. The first factory that was using electrospinning was built in 1939 in the city of Tver to manufacture BF filters (military filters), [Filatov, 1997]. Mass production in other factories was initiated in 1964.

The first patents on electrospinning were probably published in 1902 [J.F Cooley, US Pat. 692,631 and W.J. Morton, US Pat. 705,691]. Developments made by A. Formhals in 1934 [U.S. Patent 1,975,504] opened a door to commercialization. The cited work was performed on electrospinning from liquid solutions. Electrospinning from a melt was first patented by C.L Norton in 1936 [U.S. Patent 2,048,651]. However, Donaldson was the first company that successfully introduced nanofiber technology to industrial applications in 1981. In fact, research projects on this technology were initiated in early 1970s. The nanofiber filter media, known now under the name of Ultra-Web® media reached on-road and off-road diesel engine applications in 1993. The Endurance™ filters with extended service with the Ultra-Web media were introduced in 1993. In 1995, the self-cleaning Pulse Jet Air Cleaner (PJAC™) was developed in application to military high dust concentration environments. The proprietary electro-spinning process used to make the Ultra-Web® media became a great success. The Donaldson Ultra-Web nanofiber filter media technology is now protected by over 80 issued and pending patents. Mann+Hummel [Peltz et al, 2004, 2005] and Cummins [Jaroszczyk et al., 2008] consider nanofiber media in their reduced volume filters.

Nanofiber filter media are not an emerging technology any longer. Currently, nanofiber filter media are being offered in gas turbine air inlet, engine air, cabin, fuel, water, vacuum cleaning, and other markets. Moreover, production technologies, including the patented Nanospider™ electrospinning technology offered by Elmarco is available to media and filter manufacturers. The basic benefits of nanofiber media utilization are high efficiency filters, low pressure drop penalty, more compact, long life filters, “positive” dust shedding, and decreased re-entrainment of particles. There are still challenges, such as the increase in cost, chemical compatibility, durability – process and application, nanofiber layer adhesion and uniformity, and some hazards associated with solvent removal and disposal. As the use of nanofiber filter media expands, these manufacturing issues are being aggressively addressed.

Figure 6 and Table 7 show fractional efficiency as a function of particle size and pressure drop for various basis weights of nanofibers. It can be seen in the Figure that efficiency for the most penetrating particles increases from 10 to 43% when applying only 0.05 g/m^2 of nanofibers. The increase in pressure drop is approx. 27% for this basis weight of nanofibers. However, the substrate pressure drop is usually 3 to 6 times lower than the standard HD filter media in case of the cellulose substrate. The restriction of the final product is 2-4 times lower than for the commercial HD cellulose media.

Sometimes, the technology of electrospinning of nanofibers is compared with other technologies that provide much higher fiber mass output. The most important characteristic of this process is not the weight of nanofibers delivered by the process but the fiber size and fiber uniformity. Other processes can deliver a lot of fibers, but because of submicron and micron size of these fibers, at least 10 times more fibers are needed to obtain required filter performance. In the case of electrospun nanofibers only a very low basis weight, approximately 0.02-0.07 g/m^2 nanofibers with a diameter of 100 - 400 nanometers are applied to the cellulose or synthetic substrate to offer best in class filter media performance.

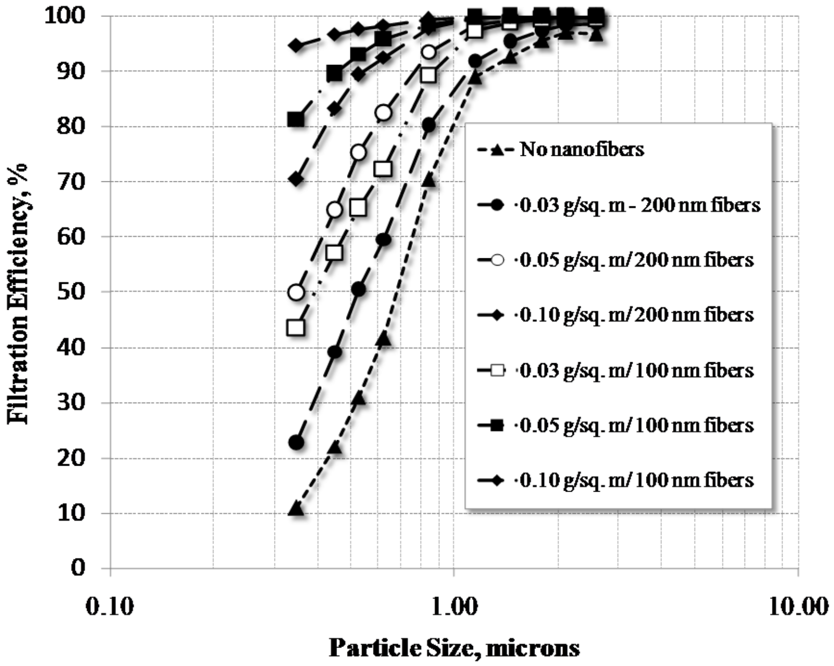

Figure 6. Fractional efficiency vs. particle size (microns) for various basis weight of nanofibers applied to a cellulose substrate

Table 7. Filter efficiency and pressure drop at media aerosol velocity of 16 cm/s = 2 50 cm/s at the filter face.

Substrate	**Nanofiber Basis Weight**	**Nanofiber Average Diameter**	**Filtration Efficiency**		**Pressure Drop**	
	g/m^2	nanometers	at 0.35 micron particle size , %	Efficiency Increase	mm of water	Pressure Drop Increase
Cellulose	No nanofibers	n/a	11	n/a	15.24	n/a
Cellulose	0.03	200	23	108%	17.53	15%
Cellulose	0.05	200	50	357%	19.3	27%
Cellulose	0.1	200	70	545%	24.13	58%
Cellulose	0.03	100	44	298%	18.8	23%
Cellulose	0.05	100	81	644%	22.61	48%
Cellulose	0.1	100	95	766%	29.21	92%

4. Conclusions:

- In-line fluted and pleated filters are offered in many different shapes that can be easily accommodated into reduced spaces of the current engine air induction systems.
- The smallest, high performance filters utilize nanofiber filter media.
- The nanofiber filter media, known now under the name of Ultra-Web® media reached the on-road and off-road diesel engine applications in 1993 and still dominate the engine nanofiber filter media.
- Nanospider™ electrospinning technology offered by Elmarco is now available to media and filter manufacturers.
- Nanofibers offer 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 nanofibers.

- The new generation of the PowerCore systems called G2 can result in a 30% reduction in size from previous axial flow filters and a 60% reduction in size from cylindrical filters.
- By integration of the intake and exhaust systems in the new Cummins QSL9, the engine meets EU Stage IIIB and EPA Tier 4 Interim off-highway emission regulations. Moreover, the new system design results in efficient combustion that leads to reduction in fuel consumption by up to 5 percent, dependent on rating. Utilized here In-line Direct Flow filters are 35% smaller then the standard air cleaners.

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