DEVELOPMENT OF HIGH DUST CAPACITY, HIGH EFFICIENCY ENGINE AIR FILTER WITH NANOFIBERS

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Abstract

Although dust-holding capacity is the primary feature of engine air filters operating in dusty environments, efficiency becomes a major factor when selecting an engine air filter. Inertial separators and high porosity or fibrous prefilters are commonly used to decrease the dust load to the main filter while high efficiency is achieved by utilizing submicron or nanofiber fibers in the main filter.

The patented multi-stage filter was designed to achieve ultra-high particle removal efficiency and dust holding capacity, and long life in dusty and on highway environments. The main (final) filter is located downstream of the prefilter. The main filter is made of pleated filter media containing nanofibers with a diameter in the range of 40 – 800 nanometers. The upstream in-line precleaner utilizing flow-through mini cyclones has separation efficiency of 95%. A high dust capacity, high efficiency prefilter can be used instead of the precleaner. The prefilter is made of vertically lapped nonwoven filter media made from synthetic fibers of different materials to fully utilize the tribological effect. The volume of the prefilter is determined by the performance required and space allotted.

This paper discusses the filter performance of high dust holding capacity engine air filters. Filter specifications, design and performance are discussed in detail. Performance characteristics of the media and full size filters were determined using on-line particle counters and the gravimetric test method. Initial and final efficiency, and dust loading performance characteristics, are provided.

Keywords: *engine air filter, multi-media filter design, nanofiber filter media, air filter performance, filter efficiency, dust holding capacity, reentrainment, testing*

1. Introduction

The role of fine, more efficient, engine filtration has mainly increased because of new engine exhaust particulate and evaporative emission regulations and the introduction of new international test standards that focus on the sizes of dust particles that penetrate the filter. Moreover, tighter tolerances and the use of on-board engine controls have dictated higher efficiency to decrease the probability of engine failure due to frictional wear and abnormal mass flow sensor operation caused by contaminate. Engine lifetime, fuel consumption, and engine emissions greatly depend on the design of all engine filtration systems that are functionally connected. To meet these high expectations, filter development has recently focused on two major subjects: reduced volume filters and ultrafine/nanofiber filter media.

Traditional surface type cellulose and surface type synthetic filter media that dominate in the engine air filtration market can deliver high dust holding capacity and high gravimetric efficiency when the dust cake is formed on the media. Therefore, understanding dust cake formation and its stability should be a focal point of the media development process. The initial efficiency and fractional efficiency for fine dust particles of traditional filter media is too low in many applications. Therefore, new high-permeability filter media that utilize fine meltblown fibers or nanofibers should be used to increase these two performance characteristics.

Recently, there is a trend caused by limited volume for engine air filters toward either reduced filter size for a stated airflow rate or increased flow rate for an air cleaner with a size comparable to a conventional panel or cylindrical filter. These needs resulted in the development of in-line fluted or pleated element air cleaners. Although there are several designs, only two major designs can be classified as the reduced volume filters; fluted or similarly constructed Channel Flow® air filters, and Direct Flow(TM) pleated filters, which were introduced to the market in 2008. In both these families of filters, high efficiency precleaners or high efficiency inline prefilters are used in dusty environments to enhance filter performance. In these designs, almost the entire volume of the filter housing is filled with filter media.

There are three major criteria that can be used to determine filter volumetric efficiency: the media utilization factor, the volumetric dust capacity, and the dust capacity index. The media utilization factor (MUF) is expressed as media surface exposed to dust in m^2 divided by the volume of the filter measured in dm^3. The volumetric dust capacity (VDC) is measured in grams of dust per volume unit that the filter occupies (g/dm^3). Dust capacity index (DCI), $d_m = m/\Delta p$; where m is the amount of dust collected by the filter in grams; Δp is the increase in pressure drop in Pascals. These criteria have the greatest values for two filter designs: the fluted and pleated, direct flow filters.

2. Reduced volume filter options

The in-line fluted filters that reached the filtration market are known as the PowerCore filters [3] and the PicoFlex® filter utilizing triangle flutes [9, 11,]. Recently, the Channel Flow® Filters [1] were also introduced to the market. The fluted design has been known for decades [16, 17, 19, 20, and many more patents]. Classical and current designs are discussed elsewhere [4-6, 15].

The inlet of all fluted designs may become clogged due to the edge phenomenon in some environments. For fluid in motion, the flute edges are solid obstacles around which the fluid moves in a manner similar to the way air moves around a jet’s wings. However, contaminant particles may be captured by the same edges due to the inertial mechanism. Because adhesive forces between the collected particles are usually greater (since they are formed of the same material) than those between the flute edge and particles, large clusters of particles are formed on previously captured contaminant. These growing particle clusters can clog the flutes. Moreover, the relatively large sealed inlet area of the flutes increases flow restriction.

In order to prevent the clogging process from occurring, Direct Flow(TM) filters were introduced by Cummins Filtration to the market in March 2008. The design is shown in Fig. 1 In the Direct Flow design, the contaminant will not clog the filter inlet because there are multiple flow faces that allow contaminant to flow directly into the end of the filter as well as around the side of the pleated media (Fig. 1). The angled gaps between the individual filter elements form flow passages that make it possible for contaminant particles to enter the plated material through the filter front side between the alternately sealed pleats and through the space above or below the element. Therefore, the filter front side stays open to the flow and filter media surface is loaded with the particles.

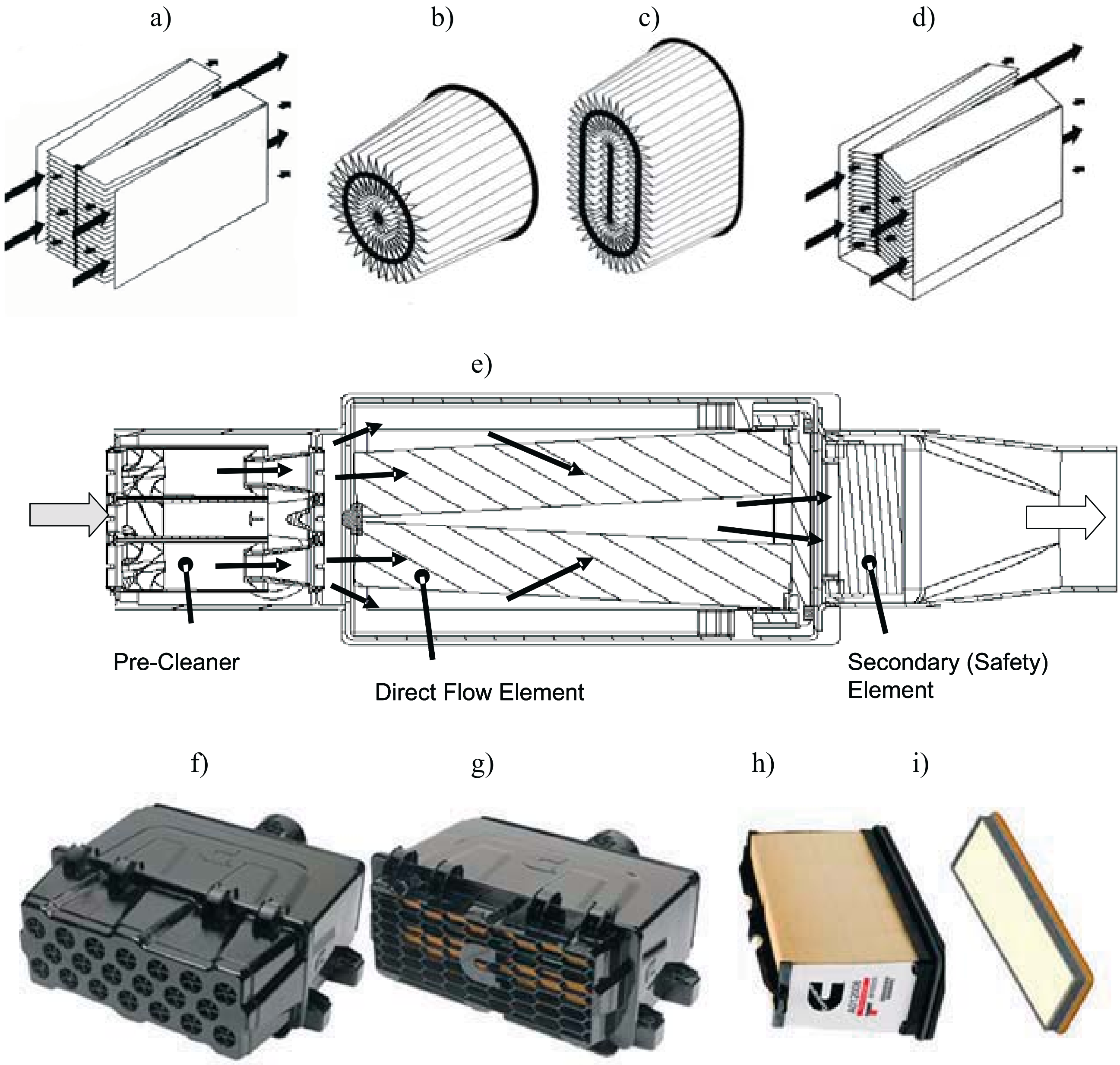

Fig. 1. Schematic and full view of Direct Flow filters; a) flow pattern through a rectangular filter with 2- filter elements, b) multi cylindrical filter, c) elliptical multi element filter ,d) filter element with skewed pleats, e) schematic view of filter assembly, f) Direct Flow filter with through flow cyclonic precleaner, g) Direct Flow filter with inlet grate, h)filter element, i) secondary (safety) filter

The flow direction shown in the Figures 1 a-d can be reversed. In both orientations, large massive particles will reach the end of the pleat due to their high inertia allowing smaller particles to be collected on media surface. In other words, the space between the pleats is gradually filled up with contaminants starting from the end of the pleat. This means that the gaps between the individual elements in both multipanel and multicylindrical designs allow free passages for aerosol in case the inlet of the pleat block is clogged by an excess of sooty or wet dust particles. Moreover, because of the high value of media utilization factor, approx. 0.8. vs. 0.68 for commercial fluted filters [4], the thickness of the dust cake is smaller, resulting in a lower pressure drop increase due to dust deposition.

The coupled filtration unit shown in Fig. 1a can be configured to obtain a modular design. Dimensions of such a unit can be modified incrementally as the flow rate increases, filtration performance specifications (increases in capacity or efficiency) change or environmental conditions (i.e., dust concentration) dictate. The combined filter is sealed in the housing with a gasket permanently attached to the multi-element outer perimeter, or permanently attached to the filter and the housing. The latter design is an option of having a disposable filter.

Fig. 1d shows a design that utilizes skewed pleats. When a layer of ultra fine fibers in the submicron or nano range is applied to the influent side of the main filter media, a „positive contaminant shedding" process may take place due to the filter natural vibration caused by the machine that the filter is attached to. The angled pleats allow for better self-cleaning efficiency of the filter media and filter elements. In all the described designs, a fixed or removable dust container can be used in high contaminant concentration environments to collect particles that fall from the spaces between the pleats.

The patented [21-26] Direct Flow (TM) filter technology provides flexibility in engine air intake design in all filter locations. It can be integrated with the engine, will occupy less space under the hood, fits the space behind the cabin, and can be used in many other locations. It can be also combined with the exhaust and crankcase aftertreatment systems to provide the necessary integration to fully manage the total engine air and exhaust gas flow.

The secondary (safety) element shown in Fig. 1, is constructed in many media and design configurations to meet customer specifications. Usually, it is made using pleated cellulose based or synthetic filter media or one layer of synthetic media. It allows the primary filter to be serviced while the engine is idling without fear of system contamination.

Flow turbulences that usually develop in the ducting transition, sudden contraction or sudden expansion areas 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:

$$\Delta p = \zeta \frac{\rho \bullet v^2}{2}, \tag{1}$$

where:
ζ - pressure loss coefficient,
ρ - air density,
v - air velocity.

Turbulence can be reduced by minimizing these transition spaces.

In contrast to the fluted filters, this design also allows for the decrease of frictional losses discussed in detail by Peltz and co-authors [11]. Frictional losses are determined by:

$$\Delta p_{fr} = \frac{s_0}{F_0} \bullet \frac{\rho v_0^2}{2} = \lambda \frac{\Pi_0}{4F_0} l \frac{\rho v_0^2}{2} = \lambda \frac{l}{4R_h} \frac{\rho v_0^2}{2}, \tag{2}$$

where:
ζ - local coefficient of fluid resistance (pressure loss coefficient),
ρ - fluid density,
v - fluid velocity,
Π_0 - perimeter,
R_h - ydraulic radius,
s_0 - friction surface,
R_h - hydraulic radius,
F_0 - cross-sectional area,
λ - friction factor as described by Moody [10].

Because of the gaps, the value of *l* in the equation is smaller than the pleat length; therefore, the frictional pressure losses decrease. The decrease in pressure drop leads greater dust capacity. Because of the high values for friction factors in the viscous region of flow, the diameter and the length of the flutes have limited values. The flutes cannot be small in diameter and long. These limitations are much less rigorous for Direct Flow filters. Fig. 2 shows dust capacity for commercial fluted filters and newly introduced Direct Flow filter having approximately the same volume.

The precleaner shown in Fig. 2, can be optimized for targeted environments. Typically, its separation efficiency is approximately 95% as measured using ISO5011 standard procedure. It can be replaced, when needed, by high performance prefilter made of nonwoven media made of parallel, triboelectric fibers [27]. Example of this prefilter performance is shown in Tab. 1.

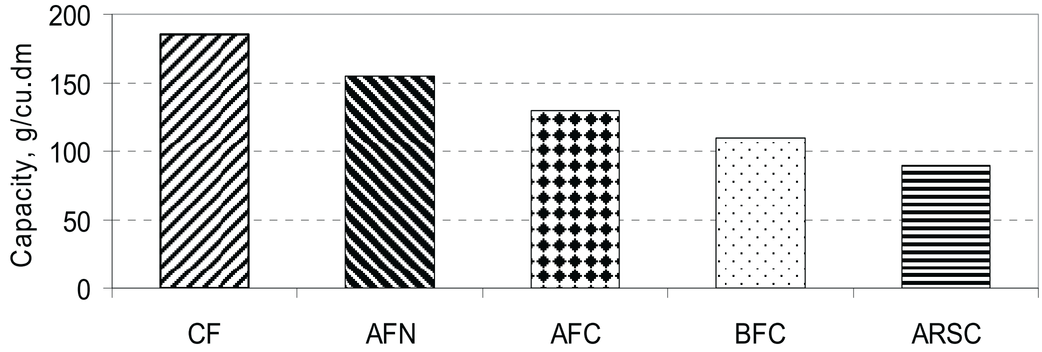

Fig. 2. Dust capacity of fluted and Direct Flow Filters, CF - Direct Flow filter, HD cellulose filter media, AFN company A, commercial fluted filter, nanofiber filter media, company A, commercial fluted filter, cellulose filter media, BFC - company B, commercial fluted filter, Cellulose filter media, ARSC - company A, commercial radial seal cylindrical filter

Tab. 1. Comparison of filter performance for a panel filter made of cellulose filter media and with a prefilter made of triboelectric parallel fibers (data for ISO Fine dust)

Design	Initial pressure drop, Pa	Terminal pressure drop, kPa	Efficiency,%	Dust holding capacity, g
Panel element with a prefilter with thickness of 25 mm and basis weight of 416 g/m^2	144.4	5.033	99.993	505.9
Panel element only	134.4	5.033	99.991	195.5

3. Nanofiber filter media in Direct Flow filter applications

When there is a need for a very compact filtration system with high efficiency for fine particles and low initial pressure drop, nanofiber media are commonly used. Nanofiber media can used to produce extremely high efficiency filters with lower pressure drop than currently available technologies resulting in volumetrically efficient systems that can fit into available space. Fig. 3 shows nanofiber filter media fractional efficiency. Nanofiber filter media were developed using cellulose substrate and less than 0.1 g/m^2 of fibers with diameters smaller than 300 nm, thickness of 0.3 mm, and a Frazier permeability of 21 cm/s. The permeability is approximately 2.5 greater than the typical media used for commercial HD media applications (trucks, construction equipment, etc.).

The fractional efficiency of the commercial nanofiber filter media (Fig. 3) is practically the same as high quality HD cellulose media. It has lower efficiency at 3 cm/s than the developed media at 20 cm/s. In fact, when a full size filter was loaded with ISO ultrafine dust (0-10 microns), patches of dust particles downstream of the filter were noted. This means that a quality assessment of nanofiber filter media is even more critical than for the classical cellulose filter media. The classical HD media have lower permeability and work at lower aerosol velocities; therefore, the probability of reentrainment of larger, the most damaging particles for engines, is relatively low. When high permeability substrate is used, nanofiber uniformity is the major objective of high quality nanofiber production line. Fig. 4. shows examples of good and unacceptable nanofiber uniformity. Good quality nanofiber layering results in uniform dust cake distribution (Fig. 4a-b) resulting in high efficiency.

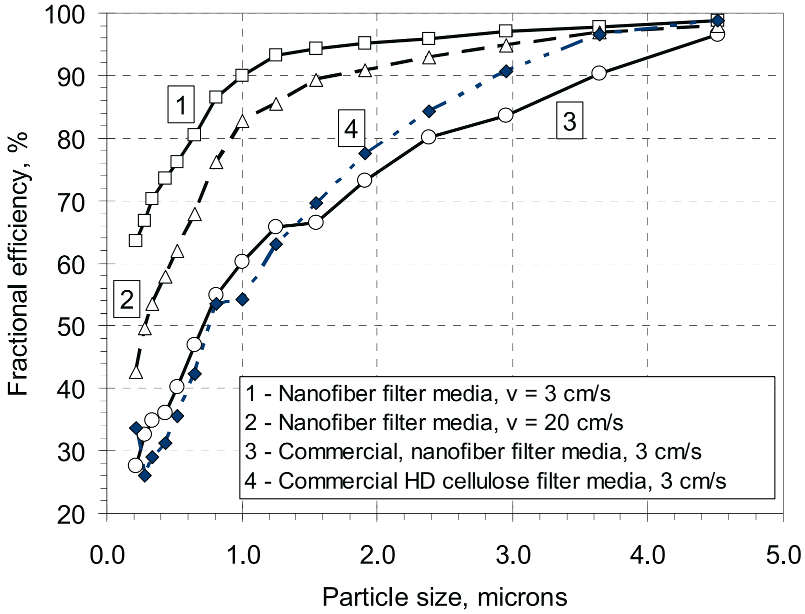

Fig. 3. Fractional efficiency of pleatable filter media

The basic understanding of the filtration mechanisms are not well known at the nanofiber scale. The classical fluid dynamics mathematical models used in the Continuum region of the filtration process do not apply to the slip flow that takes place around nanofibers. This region, described by large Knudsen numbers, requires a different approach such as the lattice-Boltzmann method. Tab. 2 describes the major parameters of engine air filtration, while Tab. 3 shows classification of filtration process in nanofiber filter media. The ratio of nanofiber diameter to cellulose fiber diameter is approx. equal to 1:130. This results in enormous surface area of 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.

Fiber diameter is the main variable responsible for filter efficiency and pressure drop. Efficiency increases rapidly with decreasing fiber diameter. For instance: using 1 μm fibers instead of 50 μm leads to a increase in filter efficiency by a factor of 2000 [14]. The efficiency would increase even more drastically when nanofibers are utilized. Unfortunately, pressure drastically increases with decreasing fiber diameter in the classical region of filtration that can be described by the Navier- Stokes equation. Media with nanofibers provides significantly higher efficiency, especially in the initial stage of the filtration.

Tab. 2. Classical engine air filtration

Dimensionless Number	Range of Values	Conditions
Reynolds (Re)	0.0007-20	d_f = 1-100 μm, v = 1-300 cm/s
Knudsen (Kn)	0.013-0.0013	d_f = 1-100 μm
Stokes (Stk)	0.004-651,000	d_f = 1-20 μm; d_p = 1-200 μm v = 1-100 cm/s; ρ_p = 2.65 g/cm^3

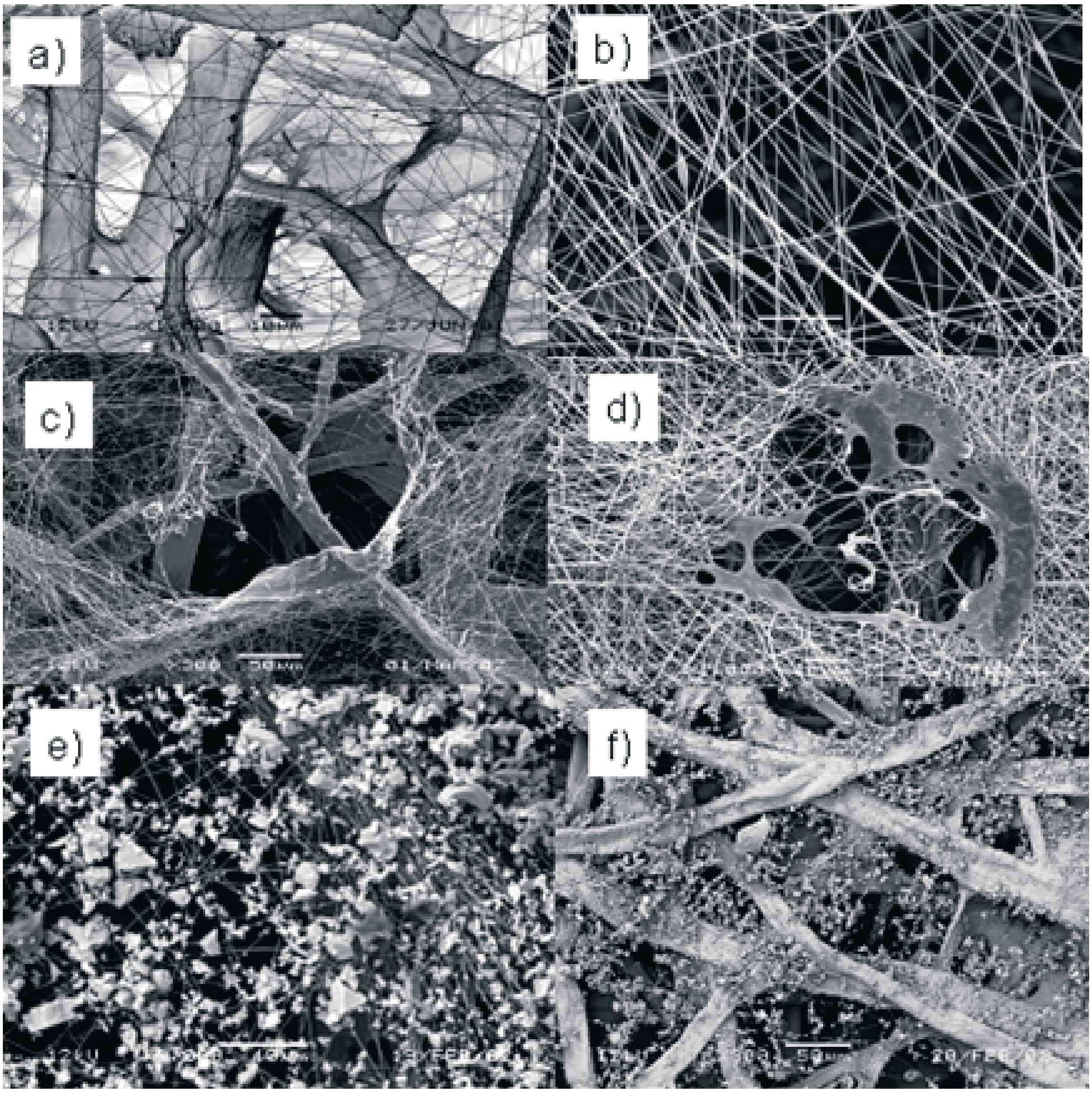

Fig. 4. Uniform (a and b) and non-uniform (c and d) nanofiber and dust cake distribution (e and f)

Tab. 3. Filtration with nanofibers

Free molecule	Transition	Slip flow (Cunningham)	Dimensionless Number
Kn > 10	Kn = 10-0.25	Kn < 0.25	Re < 0.0007
d_f < 65 nm	d_f = 65-400 nm	d_f > 400 nm	Stk < 0.004

where:

$Kn = \frac{2\lambda_a}{d_f}$ - Knudsen number,

$\lambda_a = 0.0653$ μm - the mean free path of air molecules; under standard conditions and is inversely proportional to the pressure,

df - fiber or particle diameter.

Reynolds number, Re, is defined as:

$$\mathrm{Re} = \frac{\rho v_0 d_f}{\mu} = \frac{v_0 d_f}{\nu},$$

where:

ν0 - velocity,
ρ - air density,
μ - air dynamic viscosity,
ν_0 - air kinematic viscosity.

This number represents the ratio of inertial ($\rho v_0 d/\mu$) to viscous ($\mu v/d^2$) forces. Stokes number is the ratio of the stopping distance of a dust particle to the fiber diameter:

$$Stk = \frac{X_S}{d_f} = \frac{\tau v_0}{d_f} = \frac{C\rho_p d_p^2 v_0}{18\mu_a d_f},$$

where:

X_S - stopping distance,
τ - relaxation time (the time during which most of the change in particle motion occurs),
v_0 - particle velocity (undisturbed upstream velocity),
d_p - particle diameter,
ρ_p - particle density,
μ_a - air dynamic viscosity,
C - Cunningham correction factor.

Pressure drop significantly increases with decreasing fiber diameter since it is a function of $1/d_f^2$ in this region, until the free molecule regime is reached where pressure drop is a function of $1/d_f$, [14]. In general, the larger the Knudsen number, the lower the pressure drop [14]. Pressure drop in the free molecule and slip regions is a function of $1/d_f$ [2, 12-14]. 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.

Because of the dependency of efficiency and pressure drop on fiber size and because of slip flow at fiber surface, sub-micron-sized nanofibers become highly desirable for filtration applications [7]. However, it should be understood that in areas where the specified efficiency for small particles is low, there is no need for nanofiber filter media. Nanofibers would be rather unsuitable for such application. Since nanofibers are very good collectors of small particles, a very dense dust would be formed them resulting in drastic pressure drop increase. Therefore, a careful analysis of filter dust operational conditions is necessary before any decision concerning the filter media is made. There are several theoretical models that are useful in making this decision. Löffler [8] predicted the increase of pressure drop with time.

$$\Delta p_{dl} = \Delta p_m + \frac{E_f \cdot \mu \cdot v^2 \cdot t \cdot c}{k_{DC} \cdot \rho_d \cdot (1 - \varepsilon_d)}, \tag{3}$$

where:

Δp_{dl} - pressure drop of dust-loaded filter element,
Δp_m - media pressure drop,
E_f - filter efficiency,
μ - air dynamic viscosity,
v - air velocity,
t - filtration time,
c - dust concentration,

k_{DC} - dust cake permeability,
ρd - dust density,
ε_d - porosity of the dust cake.

Pressure drop, in this case, increases linearly with time and dust concentration and with the square of velocity. Because the air permeability decreases for dust cakes formed by fine dusts, pressure drop should increase for these dusts. This equation does not include structural changes of the filter caused by dust deposited inside the filter media.

4. Conclusions

- Direct Flow(TM) filters have been recently introduced to the engine filtration market to extend the options of in-line reduced volume filters,
- The purpose of this design is to achieve high value of media utilization factor, smaller, more compact components while maintaining a long life,
- Direct Flow(TM) filters provide high filtration performance while occupying less space. Moreover, the contaminant will not clog the filter inlet because there are allowable contaminant passages around the individual filter cylinders or panels. The angled gaps between the individual filter elements form flow passages that make it possible for contaminant particles to enter the plated material through the filter front side between the alternately sealed pleats and through the space above or below the element. Therefore, the filter front side stays open to the flow and filter media surface is loaded with the particles,
- It was shown that nanofiber filter media provide high initial efficiency for small particles. However, a quality assessment of nanofiber filter media is even more critical than for the classical cellulose filter media since nanofiber filter media permeability is usually higher than of the standard cellulose media. The classical HD media have lower permeability and work at lower aerosol velocities; therefore, the probability of re-entraining the larger, most damaging particles is relatively low.

Acknowledgments

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