RECENT ADVANCES IN ENGINE AIR CLEANERS DESIGN AND EVALUATION

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Abstract

The development of engine air cleaners is based on filter performance requirements, engine operational environment, available space, filter media properties, and filter element technology. The design process includes analyses of theoretical and empirical models describing precleaner and filter media separation/filtration performance and airflow in filter housings and through filter elements. Filter media are selected based upon these models and simplified laboratory tests. Since many new motor vehicle designs offer extremely limited space for an engine air induction system, this paper concentrates on new reduced-volume filters, including direct-flow fluted and pleated compact engine air filters.

The gravimetric method is still commonly used in engine air filtration technology for air cleaner, filter element, and filter media testing. However, a new test method for fractional efficiency measurements is in the final development stage. The paper discusses this new method and provides data on filter gravimetric and fractional efficiencies.

Keywords: *engine air cleaner, filter design trends, reduced volume filters, filter media, filter performance characteristics, filter evaluation, and filter test methods.*

1. Introduction

Major progress in engine air filtration in recent years has made by introducing in-line, direct-flow fluted and pleated filters, new composite filter media with submicron fibers and nanofibers, completely plastic air induction systems, advanced CFD modeling, and a new method of filter performance evaluation. Because of new engine exhaust particulate and evaporative emission regulations, the role of the engine air induction system has increased. Engine lifetime, fuel consumption, and engine emission greatly depend on the air induction system design and its performance. Figure 1 shows total engine filtration and exhaust system. The mass of dust particles that penetrate the filter can be substantial in dusty environments when inefficient filters are used. For instance, a truck engine with a fuel consumption of 35 liters /100 km needs approximately 420,000 m^3 of air during 100,000 km. Given an average dust concentration in dusty or industrial areas of 100 mg/m^3, 42 kg of dust will reach the filter intake. Assuming filter efficiency of 99%, 420 grams of dust particles will penetrate the filter. This amount of dust will cause substantial engine wear. Therefore, an efficiency of 99.9% or even 99.99% is required in dusty areas. If the filter removes larger particles of road dust with a density of 2.65 g/m^3, leaving only particles with an average diameter of 1 μm, $3x10^{14}$ particles will penetrate the filter; 30% of these particles [Schilling, A., 1972] will enter the exhaust system. In other words, $9x10^{13}$ particles may reach the catalytic converter and the exhaust particulate filter. This number of particles would have an enormous effect on diesel engine exhaust particle filter lifetime and would greatly contribute to the total engine emission level.

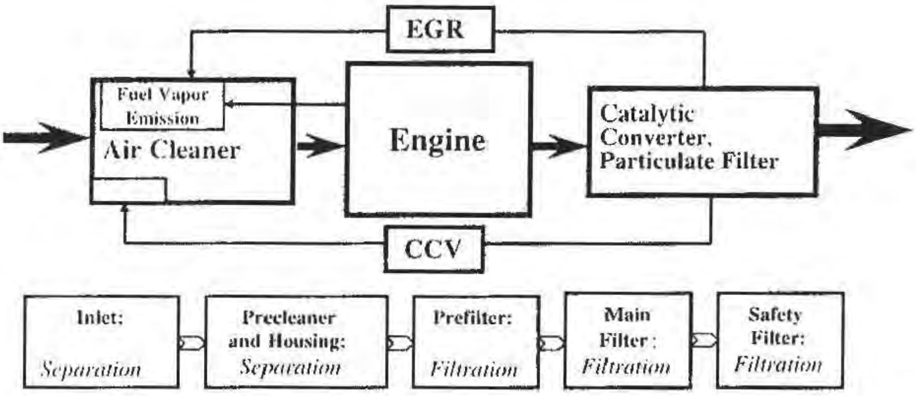

Figure 1. Total engine air and exhaust systems

2. Design trends

The need for 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 design resulted in the development of in-line fluted or pleated element air cleaners. In these designs, the entire volume of the filter housing accommodates filter media. Furthermore, new filter media with high permeability enabled size reduction of the air cleaner even further.

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 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. Turbulence can be reduced by incorporating media into the empty spaces.

The conical design [US Patent 5,106,397, 1991, US Patent Design 342, 900, 1991 – Figure 2a] that was introduced by Ford in the 1990's was one of the first designs fully utilizing the low resistance coefficient of the bullet shaped insert and the flow-straining feature of open pleats at the filter element inlet. For almost identical media surface area, 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 the panel filter counterpart. The conical filter captured 4.5 times more dust at a pressure increase of 1 kPa than did the panel filter. This indicates that filter performance characteristics greatly depend on filter design. In a study on conical and panel filter performance, it was learned that the pressure loss coefficient ζ was the major contributor to filter performance characteristics [Jaroszczyk, T., Fallon, S. L., Pardue, B. A., and K. Schmitz, 2004].

A different approach utilizing the flow-straining pleat design placed at the outlet has been recently introduced for the Heavy Duty market. In contrast to the conical filter where pleats are open at the inlet; the OptiAir™ cylindrical filter [US Patent 6,149,700, 2001 – Figure 2b] has open pleats at the filter element outlet. This pleat design enables better utilization of the housing space. The outlet of the OptiAir™ filter is significantly larger, resulting in approx. 20% lower pressure drop. This also leads to an increase in filter life. The performance can be further improved by utilizing alternate pleating and shaped inlet. This pleat design is utilized by the full flow filter [US Patent 6,391,076, 2002 – Figure 2c]. The most favorable design of this filter contains unlocked pleats at the upstream and downstream ends, allowing the air to flow relatively straight without changing its direction. The main filter has a tandem-radial seal. The downstream end seal is on the outer perimeter while the upstream seal is on the inner perimeter. The shape of the filters can be cylindrical or conical.

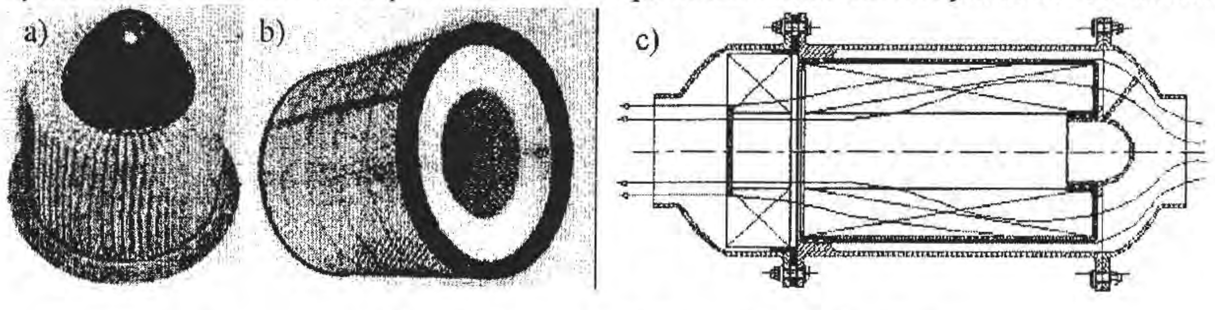

Figure 2. a) Conical, b) OptiAir™, and c) full flow filters

In-line or reduced volume, those having a high media utilization coefficient, are a relatively new family of engine air filters gradually reaching the OEM market. An example shown in Figure 3 [Donaldson Brochure, 2002] is a well known fluted design. It has been employed mainly in applications to trucks, construction equipment, and agriculture. Several companies had tried to reach these and military applications in 1980s and 1990s; however, these companies were less successful. PicoFlex® (Figure 3b) utilizing triangle flutes [Mann+Hummel, Publication 19 941 en 1203, Diesel Progress, North American Edition, 2004; Peltz, A., Durst, M., Moser, N., and V. Hensel, 2003] has recently been introduced to the market. The fluted design has been known for decades [US Patent 2,210,397,1940; US Patent 2,599, 1952, US Patent 3,025,964, 1962; US Patent 4,259 1981, and many more patents]. The common names of these filters are circular [Pratt R. P., 1985], spiral-wound, capillary, and corrugated filter.

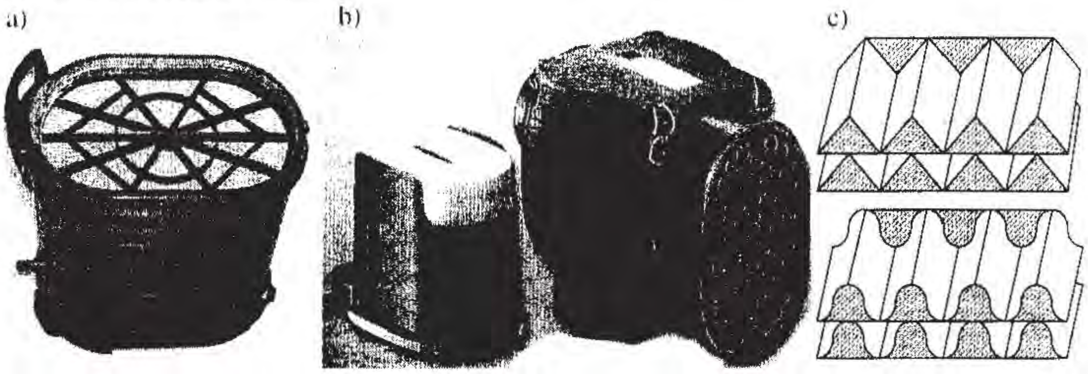

Figure 3. a) PowerCore, b) PicoFlex®, and c) flute shapes

Since 2000, a new family of in-line air filters has been patented. The design utilizes alternating pleating technology. The corrugated axial filter with simple fold pattern [US patent 6,238,561, 2001] is shown in Figure 4a. In this design, conventional pleating technology is utilized. One edge of the pleated media is tightly attached to a flat sheet of the same type of media by means of an adhesive to form a triangle base. The other triangle base of the prism is formed when the second edge of the pleated media is attached to the other side of the flat sheet media by means of an adhesive during the process of making panel or spiral wrap filters. Dust holding capacity increases for this design due to more uniform aerosol flow field and maximum use of filter media surface. The optimized flow channels have lower pressure drop. Smaller sealing edges (instead of big open ends) use much less adhesive material and also make leakage less likely. Triangular prism flutes are geometrically more stable and are harder to compress.

The newest in-line designs utilizing alternating pleating technology are: Direct Flow Filter [U.S. Patent 6,375,700, 2002], Multi-Panel Fluid Filter with Equalized Contaminant Passages [US Patent 6,482,247, 2002], and Multi-Element Cylindrical Fluid Filter with Equalized Flow [U.S. Patent 6,511,599, 2003]. Using alternating pleating technology in Direct Flow design (Figure 4 b) is a solution enabling the use of high-speed rotary pleaters. The multicylindrical and multi-panel systems can be configured with several individual elements. Such elements can be added as flow rate increases, filtration performance specifications (increases in capacity or efficiency) change or dust concentration increases. Because of the high value of media utilization factor [Jaroszczyk, T, Fallon, S. L, Pardue, B. A., and K. Schmitz, 2004], the multipanel and multicylindrical pleated design offer a more compact solution to air intake system design. Moreover, 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.

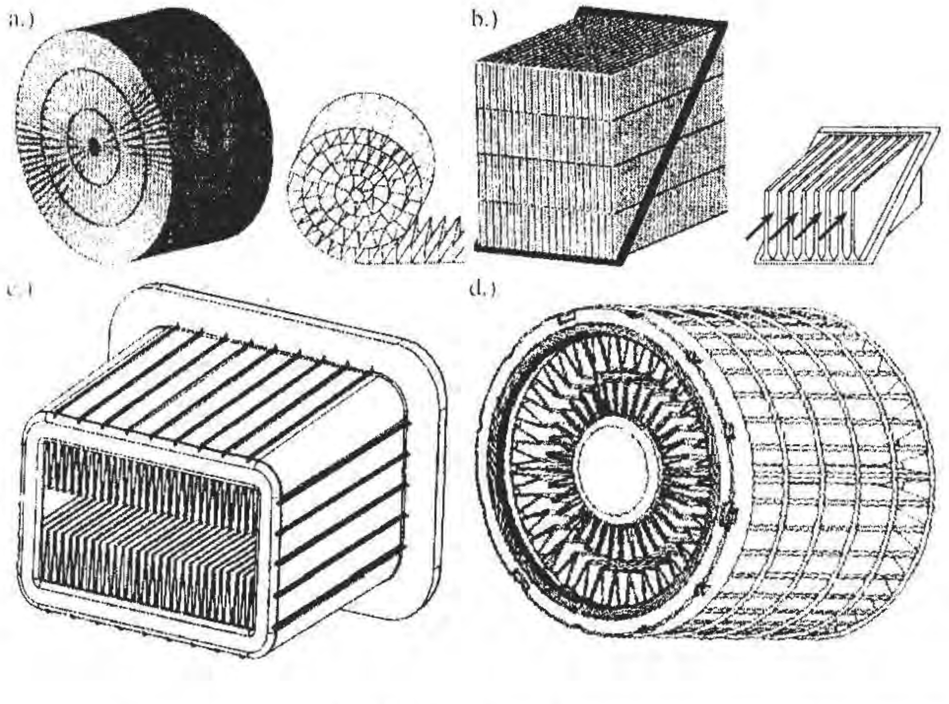

Figure 4. a) Corrugated axial filter, b) direct flow filter, c) multipanel, and d) multicylindrical

The inlet of all fluted, direct flow, and simple fold pattern filters may become clogged due to 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 an aircraft wing. Contaminant particles may be captured by the leading 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. hese growing particle clusters can clog the flutes and edges of pleated elements without the gaps between the individual elements. A partial solution to the clogging problem is to use a precleaner in front of the fluted element. However, this design substantially increases the cost of the air cleaner. Both the multi-panel and multi-cylindrical filters include gaps between the individual elements enabling free passages for aerosol in case that the front of the pleats is clogged by an excess of sooty or wet dust particles.

The multipanel and multicylindrical designs can incorporate several individual filter elements. Determining the number of elements is based on flow rates.The length and other filter dimensions are optimized to utilize the limited space available for the air intake system. Using one pleat height for all individual filter elements simplifies filter design and lowers the cost. Moreover, these two designs can be configured to a cylindrical, oval, and rectangular shape while the fluted design offers only cylindrical and oval designs.

One of the challenges for designers of the in-line filters is the location of the safety filters. The safety element is required in Heavy Duty applications by many OEM customers. Its role is to allow the primary filter to be serviced without fear of system contamination. It can also protect the engine should the main filter fail. Simple safety filters built using one layer of lower efficiency/low capacity thin synthetic media, or as a pleated cellulose or synthetic filter media are placed inside the classic cylindrical filters. More complex designs are needed for the Open Flow Filter with Safety Element called OptiAir™ filters [US Patent 6,416,561, 2002]. Still, they can be placed inside the main filter. There is no such space available in in-line filters. Therefore, the safety filters must be positioned in the filter housing behind the main filter. This approach results in increasing the air cleaner volume. In other words, space saving may be reduced in some of the "compact design" filters. Moreover, the location of the safety filter increases the cost of the air cleaner.

Some of the commercially available designs use a layer of a prefilter-type inexpensive synthetic nonwoven media that do not meet the requirements of generally acceptable safety filters. Because of the very high flow velocity in the one-layer synthetic media, dust reentrainment can reach its avalanche stage [Löffler, F. 1972; Jaroszczyk, T., Fallon, S. L., and B. A. Pardue, August 2002; Leith, D., and M. J. Ellenbecker, 1980; Jaroszczyk, T., Fallon, S. L., and B. A. Pardue, June 2002; Jaroszczyk, T., 1987]. In other words, the safety filter may be penetrated by a large amount of dust.

3. Achievements in media development

Filter media is the key determinant of filter performance. The criteria that should be considered for media selection are: flow restriction, cumulative gravimetric efficiency, dust holding capacity, fractional efficiency, and dynamic characteristics during dust loading and media physical properties such as stiffness, strength, pleatability, moisture resistance, etc.

The most commonly used media is resin-impregnated cellulose paper, because it is low cost and has the ability to pleat into densely packed pleat blocks with a well-defined pleat shape. The ribbon-like fibers with equivalent diameters from 6-8 μm in the case of esparto, approx. 20 μm in the case of hard wood, and 30 – 40 μm fibers made of soft wood. Synthetic fibers are added to increase mechanical strength of cellulose media. Because of the relatively large equivalent fiber diameter of cellulose media, filter efficiency for small particles cannot be high.

The efficiency for fine particles can be drastically improved by applying nanofiber media to a substrate. The substrate can be either a cellulose or synthetic medium. For instance, a standard high permeability cellulose filter medium can be used for this purpose. When 0.02 – 0.2 g/m^2 of nanofibers with a fiber diameter of 100 – 400 nm is applied to the substrate, the permeability decreases by 10 – 20%. However, the fractional efficiency significantly increases. Currently, nanofiber filter media in air applications are made by means of electrospinning [Doshi, J. and D. H. Reneker, 1995, Graham, K, Quyang M., Raether, T.,Grafe, T., McDonald, B., and P. Kanuf, 2002]. This process is relatively expensive because uses mainly hazardous solvents that are the hazardous waste by product. Other methods include electrospinning of molten polymers and breaking up bicomponent fibers.

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 mobile and stationary applications, and high efficiency face masks, more than 50 years ago. Approximately two decades ago, nanofiber filter media found applications in the self-cleaning filters. "Positive" dust shading found perfect applications. The dust cake can be easily removed from the media surface due to self cleaning characteristic. Currently, the media are being offered in engine, cabin, and vacuum cleaning markets. Because the cost of the media is relatively high, from 1.5 to 5 times the cellulose media, the progress in marketing these media is moderate. Examples of synthetic, cellulose and nanofiber media structures are shown in Figure 5.

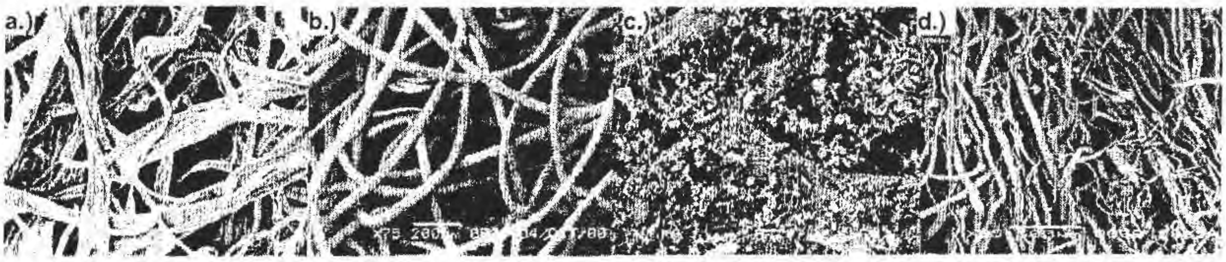

Figure 5. a) Structure of cellulose, b) synthetic, c) nanofiber filter media with captured dust particles, and d) new type prefilter

Figure 6 shows fractional efficiency of commercial cellulose media with a Frazier permeability of 11 cm/s and 7.5 cm/s at 127 Pa, and nanofiber filter media with a permeability of 8.3 cm/s at 127 Pa. The increase in fractional efficiency of the nanofiber media is substantial. Nanofibers are essential to achieving a high efficiency of particle removal at relatively low-pressure drop. For assumed filter solidity (determined porosity of the filter), the total surface area of the filter media increases with decreasing of fiber diameter. Because of that, the pressure drop of the gas flow through the fibrous structure increases for the continuum regime. However, when the fiber diameter decreases to nanometers, the gas flow is in the molecular (or transition) flow regime where the pressure drop decreases with decreasing fiber diameter since the drag forces are smaller for nanofibers. In the classical flow region, pressure drop is a function of $1/d_f^2$, while for the free molecule and slip regions it is a function of $1/d_f$ [Pich, J, 1971; Cheng, Y. S., Allen, M. D., Gallegos, D. P., and H. C. Yeh, 1988]. In other words, when fiber diameter decreases to nanometers, the gas flow is in the molecular (or transition) regime and the pressure drop decreases with decreasing fiber diameter. However, this is valid only for clean filters. When dust deposit is formed on nanofibers, this benefit of low-pressure drop reduces with increased size of the dust deposit. Moreover, the nanofibers capture very fine particles that form less permeable dust cake. In other words, pressure drop increases more rapidly for this compacted dust cake. This is one of the reasons why dust holding capacity of nanofiber filter media with high permeability is not greater than in the case of less efficient standard cellulose media. Using nanofiber filter media enable designing smaller, more compact components/long life filters (thinner media can be used - more surface area in the housing), and highly efficient air filters (initial and total efficiency) for many applications.

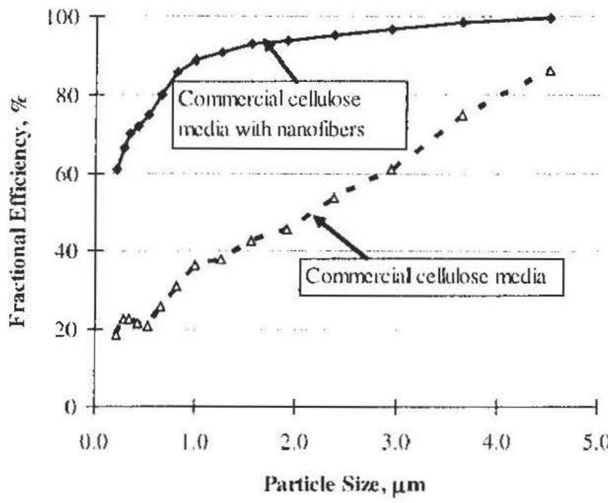

Figure 6. Fractional efficiency of nanofiber and cellulose filter media

Composite filter media made of synthetic fibers have specific physical properties that offer performance advantages over the alternatives in engine filtration. These properties include fine fibers uniformly distributed over the media surface, the ability to hold an electrostatic charge that is responsible for increased capture efficiency for small particles, high dust-holding capacity, and excellent moisture tolerance. The electrical charge on fibers may decrease over time as a result of the process of shielding and discharging by collected solid and liquid particles. Typically, this process occurs over a long time because a significant number of captured particles are needed to discharge the filter. Meanwhile, a dense dust cake is formed on the filter surface. The cake, acting as additional "filter" media, increases filter efficiency. The net effect on efficiency is difficult to predict because it depends on the media and contaminant properties. When high permeability electrostatically charge or triboelectric media are used in applications to dry dust, negative efficiency as an avalanche reentrainment of already captured particles can occur. Another issue is the "shelf" life of the charged media. We tested electrically charged media stored in a warehouse for almost two years. The efficiency did not decrease. Figure 7 shows media performance for cellulose and dual-layer, meltblown-cellulose media. The efficiency of the meltblown media is significantly higher. However, the cost of the media is sometimes prohibitive.

Synthetic media comes in a wide variety of fiber diameter, solidity and fiber materials. It can be composed of densely packed fibers which tend to form a dust cake on the surface (surface filtration) or it can be less densely packed or loftier to capture particles throughout the thickness of the media (depth filtration). Synthetic media are generally more expensive than cellulose media, but often provide better performance or better ability to withstand certain environmental conditions, particularly heat and humidity. Media thickness is a problem in the pleated filter element application. In case of cellulose media, the thickness is in the range of 0.2 – 0.8 mm while it is 1.2 – 3 mm for synthetic felts. The Frazier permeability is in the range of 6 – 40 cm/s at 127 Pa. The basis weight is in the range of 100-150 g/m^2. The media properties enable uniform pleat spacing. Therefore, the utilization of media surface is optimal.

It is also important to understand that needle punching, commonly used in nonwoven production technology results in pinhole formation that leads to particle reentrainment. In order to avoid particle seepage, air velocity must be carefully chosen. Performance of a commercial car filter made of synthetic media is shown in Figure 8. This filter collects 700 g/m^2 of ISO fine dust at a terminal restriction of 2.5 kPa and flow rate of 410 m^3/h. The initial gravimetric efficiency according to ISO 5011 standard was 99.73% while the final was 99.895 %. Fractional efficiency of the media is in the range of commonly used cellulose filter media.

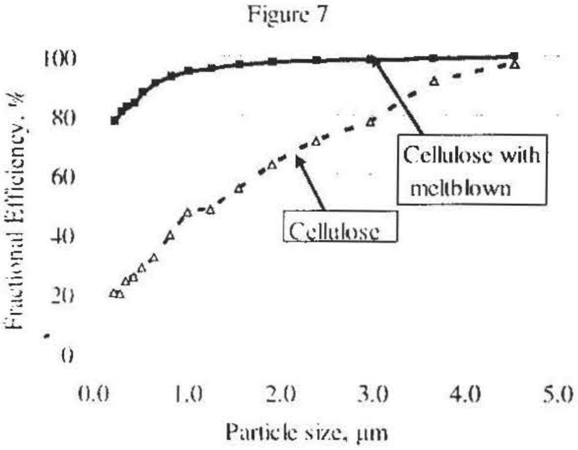

Figure 7. Cellulose and cellulose-meltblown media performance

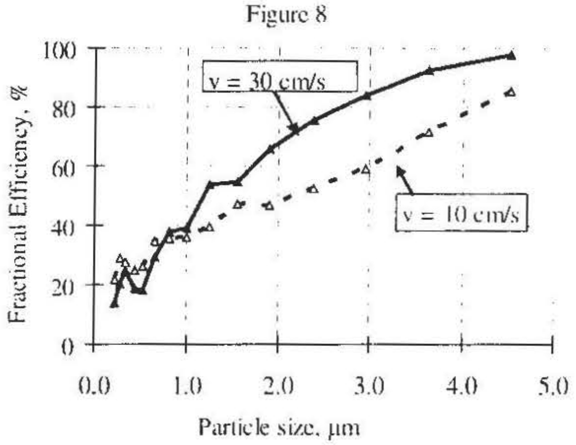

Figure 8. Synthetic filter and its fractional efficiency

High porosity synthetic media have found applications as prefilters. New media that have recently been introduced to engine filtration [U.S. Patent 6, 387,144, issued on May 14, 2002] are formed with a convoluted or pleated internal structure (Figure 6d). The thickness of the filter media is equivalent to the convolution or pleat depth. The media retains its form because of thermal bonding of the fibers on the pleat faces. This enhances the media's compression resistance and increases its rigidity to the extent that no additional backing is required for the media to retain this shape. This bonding method eliminates the direct "through the media" path associated with needling, thereby preventing the direct penetration of contaminants. The convoluted internal structure causes the majority of fibers to be oriented in a direction parallel to fluid flow. Advantages to this co-directional flow/fiber arrangement are longer residence time for particles passing through the media, reduced particle bridging, and higher collapse strength providing increased capacity and efficiency.

4. Testing and criteria for filter selection

The criteria that are typically considered for engine air induction system design and selection are the performance characteristics: pressure drop, Δp, initial, Δp_i, and terminal, Δp_t; filter gravimetric efficiency, E_g, initial, E_{gi} and cumulative, E_{gf}; and dust holding capacity, Δm. Sometimes, the maximum size of penetrating particles (or fractional efficiency, E_f), and dynamic characteristics during dust loading (leak, seepage, load distribution, reentrainment) are included in the analysis.

It is required that any engine air filter should achieve maximum dust holding capacity, Δm, which represents maximum life in service, while obeying two other requirements: $E \geq E_{min}$ 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. Unfortunately, the size of the filter is not included in the listed criteria.

Flow restriction is measured directly and is expressed in Pa, mm of water, or inches of water. A low pressure drop is necessary for optimal engine performance. Usually, the maximum acceptable engine power loss due to restriction of the engine air induction system is 2-3%. The maximum air intake system restriction is generally 3.8-5 kPa for gasoline engines, 5-7.6

kPa for turbocharged diesel engines, and 6.3-7.6 kPa for naturally aspirated diesel engines [Morton, D. W., 1970].

The initial gravimetric efficiency is not measured for a clean filter, as many users assume. In fact, it is determined after the addition of 11 g/m^2 of test dust [ISO 5011]. According to this standard, full life gravimetric efficiency and dust capacity tests are determined at a restriction of 6 kPa or as specified by the user. Values of initial gravimetric efficiency for eight cylindrical truck filters tested with ISO fine dust was in the range of 99.12 – 99.45% while final gravimetric efficiency values, at 2.5 kPa terminal pressure drop, ranged from 99.97 to 99.99% [Jaroszczyk, T., Fallon, S. L., Liu, Z. G., and S. P. Heckel, 1999]. Because of the closeness of the values, it can be difficult to distinguish between these filters based on gravimetric filtration efficiency.

Dust-holding capacity for commercial filter elements is in the range of approximately 100 – 16000 grams of ISO Fine dust with specific dust loading of up to 500 g/m^2 for cellulose media. Dust-holding capacity is the performance metric in which many filter users are most interested. High dust holding capacity typically means long filter life. In other words, fewer filters will be needed and replacement costs will be lower. This does not automatically mean that the total cost for the user will be lower. High dust capacity does not usually correspond with high efficiency. Only a combination of high efficiency and high capacity results in longer engine life and lower oil consumption, emissions and fuel consumption.

Although pressure drop and efficiency are functions of the same filter, contaminant and air flow parameters, they are considered independently. There is no standard classification for engine air cleanliness levels. Engine and motor vehicle producers specify requirements concerning air intake contaminant level by means of gravimetric efficiency. A filter's gravimetric efficiency is determined in the laboratory with standardized dusts and standardized dust concentrations of 1.0, 0.5 or 0.25 g/m^3 [ISO 5011; SAE J726 standards]. The downstream dust concentration (that penetrating the filter) is calculated by measuring the weight increase of an absolute filter composed of fiberglass. The absolute filter's filtration performance is not specified, but is classified by physical parameters. To avoid reentrainment, the maximum face velocity cannot exceed 50 m/min (83.33 cm/s = 164 fpm) [SAE J726]. The efficiency of a clean absolute filter is less than 80% for 0.3 µm dust particles and reaches 100 % for particles larger than 1.0 µm [Jaroszczyk, T., Fallon, S., and , Z. G Liu, 1998].

Despite the fact that particle size is necessary to understand the engine frictional wear process [Koffman, J. L., 1953; Pochtarov, N.F., 1957; Schilling, A., 1972; Khorshid, E. A., Nawwar, A. M., 1991; Needelman, W. M., Madhaven, P. V., 1988; Needelman, W. M, 1994], current testing procedures reveal no information about the dust particle size distribution downstream of the engine air cleaner. No standard for testing engine air cleaners includes procedures for fractional efficiency measurements. Such information is also needed for engines with electronic sensors in their air intake systems to avoid calibration problems [Jaroszczyk, T., Wake, J., and M. Connor, 1993; Poon, W.S., Liu, B.Y.H., and N. Bugli, 1997; Bugli, N. and M. Hettenhouse, 1997].

The gravimetric methods ISO 5011 and SAE are still the only test methods commonly used in engine air filtration technology for air cleaner, filter element and filter media testing. Recently, the ISO 5011 standard replaced the SAE J726 standard. In other words, there is no SAE J726 standard for testing engine air cleaners. The ISO 5011 standard shall be used now. This method does not provide information on contaminant particle size. Moreover, this method, in many cases, has inadequate precision to distinguish between filters. Since both the dust mass and its particle size are needed to estimate engine wear, the SAE J726 Air Cleaner Committee initiated work in 1994 on a test method to measure engine air cleaner fractional efficiency. The draft of the standard "Engine Air Cleaner Fractional Efficiency Technical Report" that was completed in September 2003 became ISO/TC22/SC7/WG3 N 406 working document entitled "Inlet air cleaning equipment for internal combustion engines and compressors – Fractional efficiency testing."

Fractional efficiency, E_{Fi}, %, is defined here as the ability of the air cleaner to remove airborne particles of a specified size. $E_{Fi} = \frac{C_{1i} - C_{2i}}{C_{1i}} \times 100$, where: C_{1i} = number or mass concentration of particles of specified size, i, in the influent, C_{2i} = number or mass concentration of particles of specified size, i, in the effluent.

The standard also defines dust penetration through the filter. This is probably the most important filter characteristic because it provides information on the amount of dust that penetrates the air cleaner and could enter the combustion chamber. Fractional penetration, P_i, is defined as the ratio of the number or mass of particles of specified size exiting the air cleaner per unit time to the number or the mass of particles of specified size entering the air cleaner per unit time expressed in a percentage:

$$P_i = \frac{C_{2i}}{C_{1i}} \times 100 \text{ or } P_i = 1 - E_{Fi}$$

Initial fractional efficiency is determined for a clean air cleaner before the collected aerosol has any measurable effect on the efficiency of the air cleaner under test. The method also recommends determining incremental fractional efficiency for a dust-loaded filter. It is determined at 10%, 25%, 50% and 100% of filter life. Filter life is measured as a percentage of pressure drop increase from its initial to the terminal value. An example of such test results is shown in Figure 9. The test is run at filter-specified flow rate. The specified test flow rate was 306 m^3/h. ISO 12 103 - A2 Fine test dust is recommended as the loaded contaminant while fractional efficiency is measured with potassium chloride aerosol. The fractional efficiency test aerosol is neutralized by passing it through a radioactive or other ion-generating device to reach a Boltzman equilibrium charge distribution.

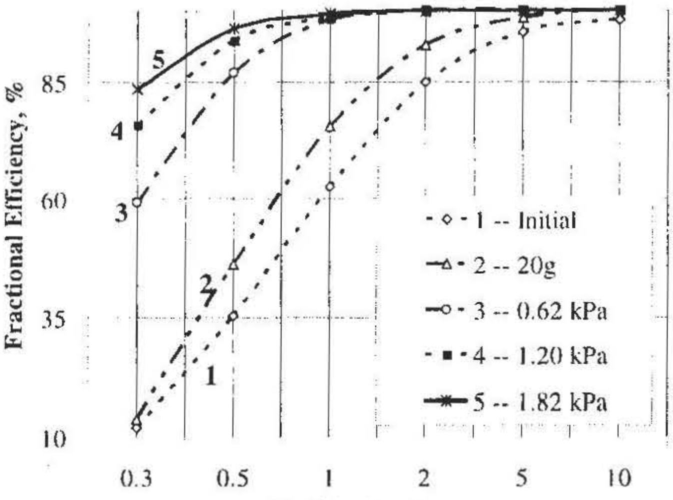

Figure 9. Fractional efficiency of a panel air cleaner with cellulose air filter element.

Fractional efficiency is measured in six ranges of particle sizes listed in Table 1. Optical particle counters or aerodynamic particle counters are recommended. Isokinetic sampling is required by the procedure. A sequential counting system with a single particle counter or simultaneous counting system with two upstream and downstream particle counters can be used for filter testing. A schematic drawing of the test setup is shown in Figure 10. This setup is similar to the SAE J726 or ISO 5011 test stand. The major difference is the HEPA inlet filter and sampling ports with particle counters.

Table 1. Ranges of fractional efficiency measurement

Channels	1	2	3	4	5	6
Optical size range, μm	0,3 – 0,5	0,5 – 1,0	1,0 – 3,0	3,0 – 5,0	5,0 – 10,0	>10,0
Aerodynamic size range, μm	0,5 – 1,0	1,0 – 2,0	2,0 – 5,0	5,0 – 10,0	10,0 – 15,0	>15,0

The gravimetric efficiency method emphasizes the mass of particles while the fractional efficiency highlights the particle number at predetermined sizes. In the gravimetric efficiency test, the test dust type must be given together with the efficiency number.

A method providing continuous gravimetric and fractional efficiency would be an ideal method for laboratory and field testing of full size filters. Unfortunately, there are no particle sensors available for this purpose. However, a Continuous Aerosol Monitoring (CAM) System with influent and effluent sensors with a flow sampling rate of 1 dm^3/min can be used to measure the filter efficiency of media samples (T. Jaroszczyk, R. H. Hoops, and G. Kreikebaum, 1987]. The general design of the test stand is similar to the fractional efficiency setup shown in Figure 10. The method uses isokinetic sampling with upstream and downstream dust sensors. The sensors continuously measure dust concentration and particle size distribution and provide information on filter performance every five minutes. This measures incremental and cumulative efficiency. The incremental efficiency is important, since it provides data on filter performance in time intervals of five minutes. Therefore, any dust reentrainment can be detected. Examples of data provided by this test system are shown in Figure 11a and 11b. Figure 11a shows efficiency for a synthetic prefilter while Figure 11b for a multi-layer synthetic car filter. The prefilter with a thickness of 20 mm was made of 6.5 denier polyester fibers (approx. 26 μm). AC Fine dust was used for testing. The particle size is approximated based on calibration using SAE fine dust. By utilizing pressure transducers, filter restriction was measured continuously.

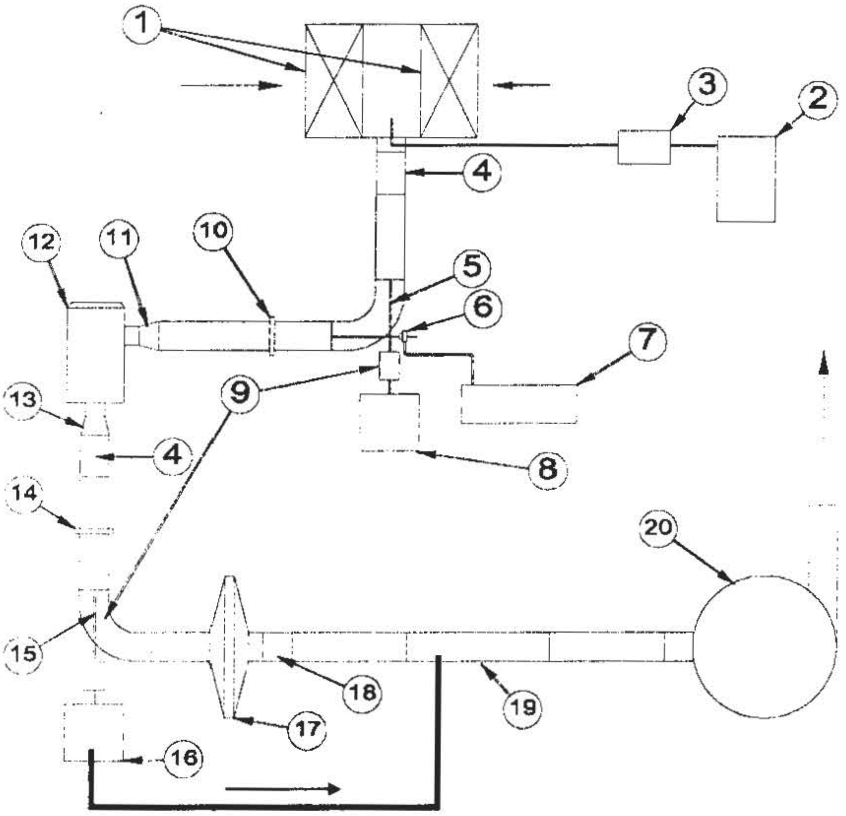

Figure 10. SAE/ISO Fractional efficiency test stand configuration

*1. HEPA Inlet Air Filtration, **2. Challenge aerosol feeder, 3.** Aerosol neutralizer, **4.** Static mixer, **5.** Upstream isokinetic sample probe, **6. Dust injector, 7.** Loading dust feeder, **8.** Upstream particle counter, **9.** Dilution (if required), **10.** Inlet piezometer tube, **11.** Inlet transition tube (if required), **12.** Unit under test, **13.** Outlet transition tube (if required), **14.** Outer piezometer tube, **15.** Downstream isokinetic sample probe, **16.** Downstream particle counter, **17. Absolute filter, 18.** Airflow straightener, **19.** Airflow Meter, **20.** Airflow pump (exhauster)*

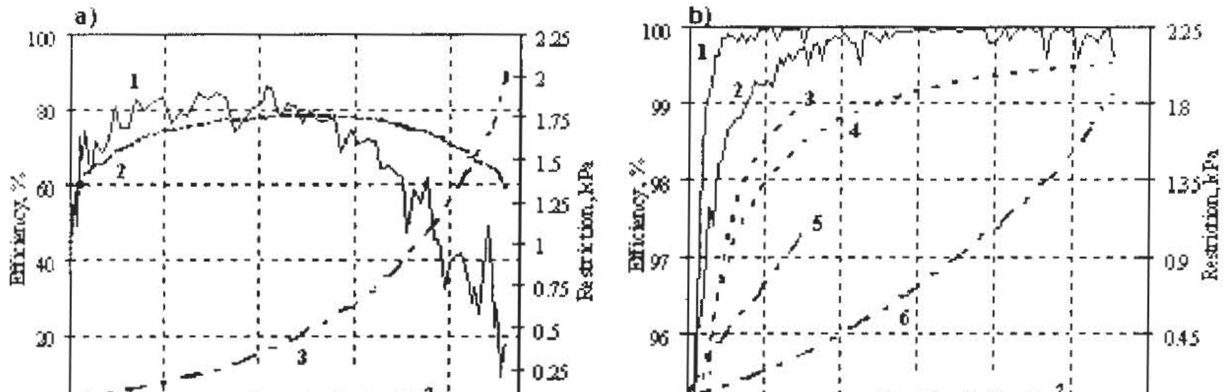

*Figure 11. Continuous gravimetric **efficiency**: a) - high porosity synthetic nonwoven prefilter (1- incremental efficiency, 2 - cumulative efficiency, 3 – pressure drop),*
*b) - multilayer synthetic car air filter media (1- incremental efficiency for AC Fine dust, 2 - incremental efficiency for AC Coarse dust, 3- cumulative **efficiency** for AC Fine dust , 4 – cumulative efficiency for AC Coarse dust, 5- pressure drop for media loaded with AC Fine dust, 6 - pressure drop for media loaded with AC Coarse dust).*

The most common filtration criterion that combines filter efficiency (or penetration) with pressure drop is the "the filtration criterion" γ [Chen, C. Y., 1955] in the form:

$\gamma = \frac{\ln N/N_0}{\Delta p}$ Where: N and N_0 are number concentration of aerosol particles; N_0, in the influent, N, in the effluent ($N/N_0 = P$ - penetration); and Δp = pressure drop across the filter. A similar criterion, called Figure of Merit, $Q = -\frac{\log P}{\Delta p}$, was elaborated by Quyang and Liu [Ming Quyang and Benjamin Y.H. Liu, 1997] and applied to all filtration regimes including continuum, slip flow, and transition regime. The higher the values of γ and Q, the better the filter. Unfortunately, both criteria are dimensional.

The gradient of pressure drop increase describes the filter clogging process in the field. Filter specification usually does not include these data. Initial and terminal pressure drop is specified instead. Filter selection practically concentrates on the initial pressure drop. Some filters with low initial restriction are rapidly clogged by a relatively small amount of dust. In order to compare filter operation in the field and laboratory, a simple coefficient was introduced [Tadeusz Jaroszczyk, Stephen L. Fallon, Jason E. Dorgan, Jerald J. Moy, Thomas P. Sonsalla, and Brad Henke, 2003] called dust capacity index, $d_m = m/\Delta p$; where m is the amount of dust collected by the filter in grams; Δp is the increase in pressure drop from initial to terminal in Pascals. The initial pressure drop is measured for a clean filter element. The index was in the range of 0.31 – 1.07 for classical cylindrical filters made of pleated cellulose paper [Jaroszczyk, T, Fallon, S. L, Dorgan, J. E, Jerald J. Moy, J. J, Sonsalla, T. P, and B. Henke, 2003]. The value increased to 2.83 in the case of similar filters with a prefilter made of nonwoven media with the majority of the fibers positioned perpendicular to the flow direction [US Patent 6 387 144, 2002]. The multi-media filters were designed for direct replacement of existing one-stage pleated filters for use in the same housing. The field tests were run for a year on trucks driven from 137,000 to 217,000 km on highways mainly in Northern U.S. The high dust capacity index of for the multi media filter in on-highway applications means that the dominant oily and sooty particles were captured by the prefilter. Therefore, the pressure drop increase of the main filter was low.

New challenges emerge when including air cleaner size in the measures used for judging filter performance. Since the volume occupied by the engine air cleaner has become increasingly constrained in many applications, new measures were introduced to compare filters [Jaroszczyk, T, Fallon, S. L, Pardue, B. A, Liu , Z. G, and K. Schmitz, 2004]:

- Media utilization factor, MUF, m^2/dm^3
- Specific dust capacity, SDC, g/dm^2
- Volumetric dust capacity, VDC, g/dm^3
- Volumetric dust capacity index, VCI, $g/dm^3//kPa$

$$MUF = \frac{A_m}{V_f},\ m^2/dm^3;\quad SDC = \frac{m_d}{A_m},\ g/m^2;\qquad VDC = \frac{m_d}{V_f},\ g/dm^3;\ VCI = \frac{VDC}{\Delta p_d},\ g/dm^3//kPa;$$

Where: Am = media surface area in m^2; V_f = filter volume in dm^3 (liters); m_d = mass of dust collected in the filter; Δp_i = initial pressure drop; Δp_t = terminal pressure drop, Δp_d = differential pressure drop, $\Delta p_d = \Delta p_t - \Delta p_i$ in kPa.

Although the measures are still dimensional, they are useful in air cleaner judgment. For instance, the media utilization factor (*MUF*) for certain fluted filters has a value of 0.68 m^2/dm^3. The value for the OptiAir™ filters is in the range of 0.37 – 0.48 m^2/dm^3. The maximum value for the standard cylindrical filters is in the range of 0.33 – 0.43 m^2/dm^3. However, *MUF* for a cylindrical pleat block of the commercial cylindrical filter is approximately 0.65. Media thickness is approximately 0.6 mm while media thickness for the fluted filter is approximately 0.2 mm. Therefore, *MUF* for a pleat block of a cylindrical filter using thin media would practically reach a value of over 1 m^2/dm^3. In fact, the *MUF* for the pleat block of some OptiAir™ filters is in the range from 0.5 to 1.48 m^2/dm^3, depending on media thickness and pleat density. This number is difficult to reach with fluted reduced-volume filters. Because the multipanel and multicylindrical direct flow filters use pleat blocks instead of flutes, the *MUF* for these filters can reach greater values than these of fluted filters. In other words, the multielement direct flow filters have certain performance advantages over fluted designs.

In all filter designs, the space available for airflow is drastically reduced if media thickness is excessive. Usually, the average thickness of cellulose filter media is in the range of 0.25 – 0.8 mm. With this thickness, the typical pleat density is in the range of 20 - 55 pleats per 100 mm. The thickness of synthetic media is usually greater than 1 mm, often in the range of 1.5-2.5 mm thickness. In order to attain reasonable pressure drop, synthetic media permeability must be increased. The value of Frazier permeability is usually greater than 100 fpm (50 cm/s) at 127 Pa. Because of the high porosity of the synthetic media, dust reentrainment is likely at higher dust loadings. However, the thickness can be reduced while permeability increases and efficiency maintained by using nanofiber filter media.

Specific dust capacity, m_d is measured in grams of collected dust per 1m^2 of media in the filter at the terminal pressure drop. This depends on media performance, filter design and flow rate. Because it is not directly linked to filter volume, a volumetric-specific capacity was defined as a ratio ofthe mass of dust collected in the filter at the terminal pressure drop to the filter volume. The greatest values of the volumetric dust capacity index were achieved for the PowerCore filters.

5. Conclusions

- Major progress in engine air filtration in recent years was made by introducing in-line, direct flow fluted and pleated filters.
- The purpose of these designs was to achieve smaller, more compact components while maintaining a long life or to incorporate larger media surface area to gain higher dust holding capacity.
- The fluted and pleated reduced-volume filters can provide high filtration performance while occupying less space.
- The most commonly used media are still resin-impregnated cellulose paper, because it has the low cost and the ability to pleat into a densely packed pleat block with well-defined pleat shape.
- Nanofiber filter media have reached the OEM market. They offer high initial efficiency for small particles. Because the solvent electrospinning method dominates nanofiber production technology, the media are relatively expensive.
- Composite filter media made of synthetic fibers with specific physical properties have found applications mainly in small filter markets. Some of the media have the ability to hold an electrostatic charge, which results in increased capture efficiency for small particles. However, the electrical charge on fibers may decrease over time because of the process of shielding and discharging by collected solid and liquid particles. Dust reentrainment is likely to occur in the case of high porosity media leading even to negative efficiency.

- The gravimetric methods ISO 5011 and SAE are still the only test methods commonly used in engine air filtration technology for air cleaner, filter element and filter media testing. Recently, the ISO 5011 standard replaced the SAE J726 standard. In other words, there is no SAE J726 standard for testing engine air cleaners.
- The SAE J726 Air Cleaner Committee has recently developed a draft of a new fractional efficiency test method. The draft became ISO/TC22/SC7/WG3 N 406 working document entitled "Inlet air cleaning equipment for internal combustion engines and compressors – Fractional efficiency testing" in October 2003.
- The fractional efficiency method can give useful information about the performance of the filter particularly in the early stages of filtration. It may be useful for detecting system leaks and contaminant reentrainment in the later stages of filtration.
- New criteria: media utilization factor, volumetric dust capacity index, and volumetric specific capacity were introduced in 2004 to help in filter classification and selection.
- There is no universal, dimensionless criterion or method for media classification.

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