NEW DEVELOPMENTS IN DIESEL ENGINE CRANKCASE EMISSION REDUCTION - EQUIREMENTS, DESIGN AND PERFORMANCE

Tadeusz Jaroszczyk[1], Christopher E. Holm[2], Stephen L. Fallon[3]

[1]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.: +1 608-873-2423, fax: +1 608-873-1550, e-mail: tad.jaroszczyk@cummins.com

[2]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.: +1 608-873-2423, fax: +1 608-873-1550, e-mail: christopher.e.holm@cummins.com

[3]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.:+1 608-873-3835, fax: +1 608-873-1550, e-mail: stephen.l.fallon@cummins.com

Brian W. Schwandt[4], Leon Gradoń[5], Bryan P. Steffen[6]

[4]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.: +1 608-873-1558, fax: +1 608-873-1550, e-mail: brian.w.schwandt@cummins.com

[5]Warsaw University of Technology, Cummins Filtration Professor of Separation Technologies
1 Waryńskiego Street, 00-645 Warsaw, Poland,
tel./fax: +48 22 825 91 80, e-mail: gradon@ichip.pw.edu.pl

[6]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.: +1 608-873-3901, fax: +1 608-873-1550, e-mail: bryan.p.steffen@cummins.com

Michael T. Zuroski[7], Ashwin K. Koleshwar[8], Jerald J. Moy[9]

[7]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel. +1 608-873-15011, fax: +1 608-873-4332, e-mail: mike.zuroski@cummins.com

[8]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel. +1 608-873-1543, fax: +1 608-873-1550, e-mail: ashwin.k.koleshwar@cummins.com

[9]Cummins Filtration Inc. 1801 Hwy 51/138, Stoughton, WI, USA
tel.: +1 608-873-1539, fax: +1 608-873-1550, e-mail: jerald.j.moy@cummins.com

Abstract

The role of the filtration system for engine crankcase ventilation has recently increased because of new worldwide engine emission regulations. Turbocharger lifetime, engine emission, and oil consumption greatly depend on the filtration system design and performance of an open crankcase ventilation (OCV) or closed crankcase engine ventilation (CCV) system. Providing optimized solutions for these requirements dictates the development trends of separators and filters used for removal of oil and fuel mist, and solid particles generated by the engine.

This paper discusses environmental issues associated with engine crankcase emission, contaminant classification, the needs for protecting the turbocharger against contaminants, and filtration system design and performance. The design section provides analysis of theoretical models applied to coalescing filtration and oil/fuel mist separation techniques. Since there are no existing standards for these systems' performance evaluation, this paper discusses current activities at SAE and ISO on standard development. Finally, performance characteristics of a new, high efficiency depth-type filter-coalescer are described.

Keywords: *engine crankcase ventilation, coalescing filtration, depth-type filter-coalescers, filter testing*

1. Introduction

Crankcase engine emission reductions have always been needed to complete the loop for total engine emission reduction. Earlier, exhaust emissions were the primary focus of the scientific and engineering community due to governmental regulations. Now, because of additional regulations, crankcase emissions are coming under greater scrutiny. Serious research and engineering work on emissions emanating from the crankcase has mostly been performed in the last 20 years. However, much of the theoretical background regarding the removal of liquid particles, including mist, is as old as research on filtration processes. In fact, the basic filtration mechanisms were mainly verified experimentally using ultrafine liquid particles. The old DOP (**D**i-**O**ctyl **P**hthalate aerosol challenge) test is an example of a method that uses such aerosol. The main reason for using liquid particles in testing is the simple generation system. Moreover, science on liquid aerosols intensified when they were used in chemical warfare applications.

Factors stimulating the use of separation/filtration systems in CV can be classified in two categories ─ societal concerns for a cleaner environment and factors associated with engine operation and durability. The environmental issues affect governmental regulations. The engine operation standards are developed by engine producers and are the foundation for national and international standards. In both cases, advanced separation/filtration systems are necessary to meet environmental requirements or engine producers' specifications.

In contrast to classical oil mist eliminators which are usually exposed to one type of liquid contaminant, engine crankcase separators and coalescers operate at variable flow rates and in complex environmental conditions. These factors have a significant influence on system performance.

In this paper, we discuss engine crankcase contaminates, crankcase ventilation system design options, design requirements, and test methods. However, the main focus is on high efficiency filter-coalescers operating on diesel engines. Because long-life coalescers are typically required in this application, we selected a multilayer depth-type coalescer made of synthetic fibers. The physical structure of the coalescer, fiber diameter and porosity, was optimized by the utilization of mathematical models describing three filtration mechanisms: Brownian diffusion, interception and inertial impaction. Performance characteristics of the high efficiency filters-coalescers were determined on engines in real environments and in the laboratory.

2. Engine Crankcase Environment

Combustion gases that pass by piston rings during the compression stroke result in a positive pressure in the engine crankcase. These gases, termed blow-by gases, are a mixture of N_2, O_2, CO_2, CO, various hydrocarbons (HC), and H_2O. The temperature of these gases is in the range of 50 – 90° C (120 - 190° F) for a typical loaded engine. Gas flow and mechanical action of rotating engine parts generate aerosol that is mainly composed of liquid mist, oil droplets, and solid particles that are combustion or engine wear products.

The flow rate is in the range of 6.5 m^3/h for a 200 HP diesel engine, reaching a level of 16 m^3/h for 500 HP engine. The gases carry over approximately 3 – 12 g/hr of aerosol and several grams of liquid. The flow rate is a function of engine design, combustion processes, engine type, engine life, oil, fuel, environmental conditions, and filtration systems. The contaminant concentration and its size distribution also depend on these parameters.

The efficiency of filters used in a crankcase ventilation system is critical considering that crankcase emissions could represent as much as 35% of diesel engine particulate emissions [Dickson and Edge, 1995]. Today, with the advent of diesel exhaust particulate filters the percentage would be even higher. Fortunately, new efficient crankcase separation/filtration systems have been recently launched to help compensate for this change. Figure 1 shows the contaminant distribution in engine crankcase.

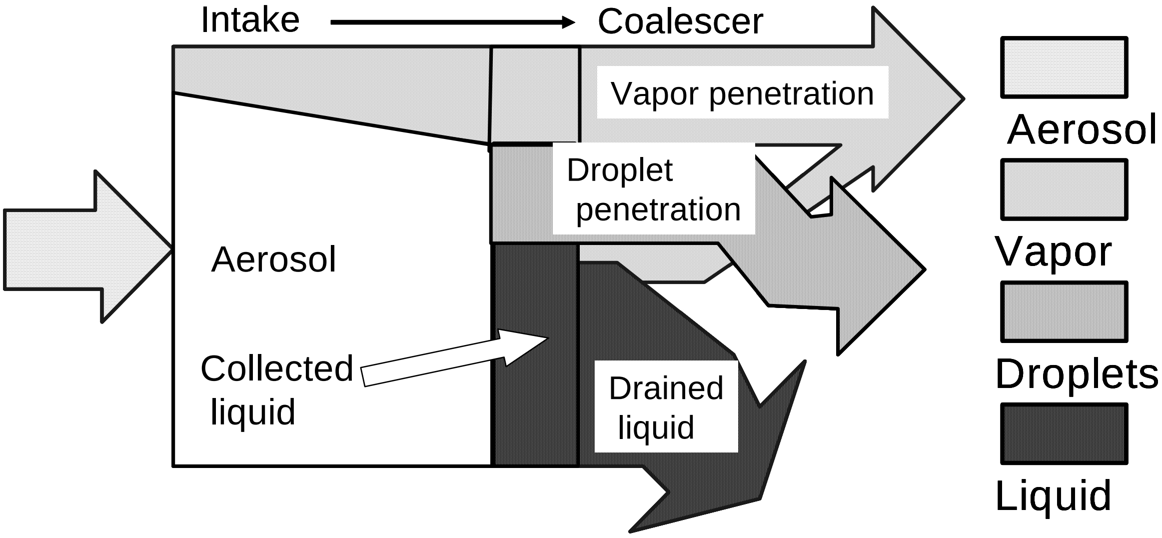

Fig. 1. Contaminant distribution in engine crankcase

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], the distribution of contaminants passing through the air induction system and entering the engine is roughly as follows: 50% goes into the engine oil, 20% remains on the walls above the piston level, and 30% passes out the exhaust. In order to reduce the contaminant concentration downstream of the filter, highly efficient filters are needed. When crankcase particles are released to the air induction system, they will contribute to total air filter penetration because of their small diameters.

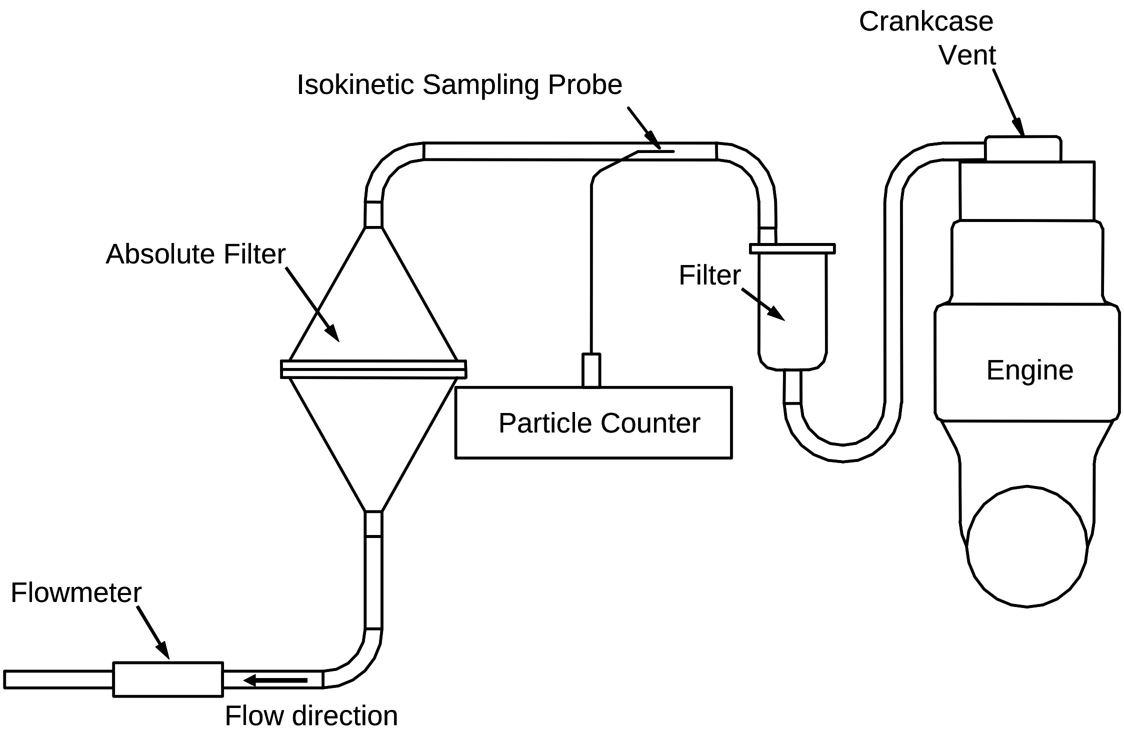

Fig. 2. Set-up for engine crankcase contaminant sampling

We used a set-up shown in Figure 2 to measure particle size distribution and concentration of crankcase emissions on a High Power diesel engine. Example aerodynamic particle size distribution is shown in Figure 3. We obtained bi-modal distributions typical of mechanically and thermally derived contaminants. However, the second mode for engine B is not well pronounced.

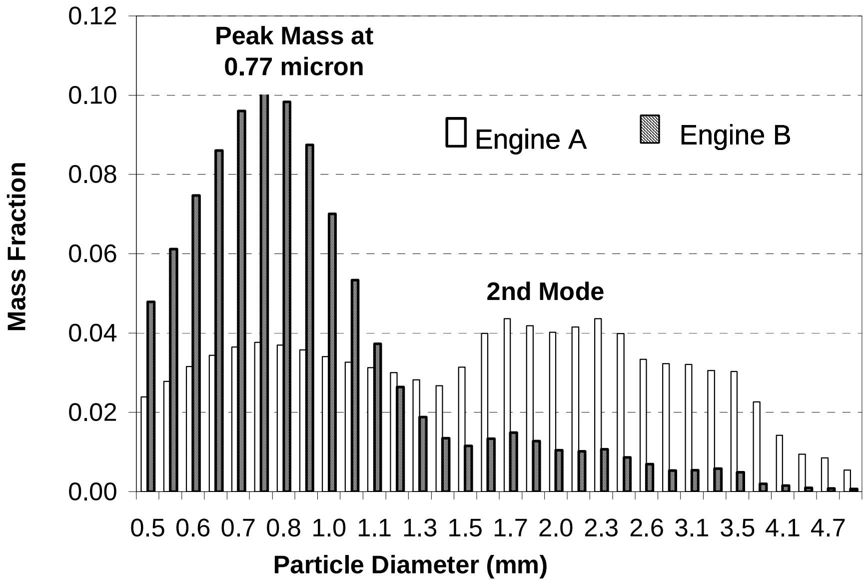

Fig. 3. Particle size distribution for two different engines

3. Crankcase Ventilation System Design Options

The two major types of crankcase ventilation systems are shown in Figure 4. In the open crankcase ventilation (OCV) system, the blow-by aerosol is vented from the crankcase to the atmosphere. In the closed crankcase ventilation (CCV) system, the aerosol is released to the engine's air intake. In both designs, the environmental parameters are similar; however, the effect is different. In the OCV, the contaminants are released to the atmosphere contributing to total engine emission. Although the crankcase ventilation emission is not yet regulated, the total emission is; therefore, lowering the contaminant concentration level from the crankcase helps engine producers pass emission tests.

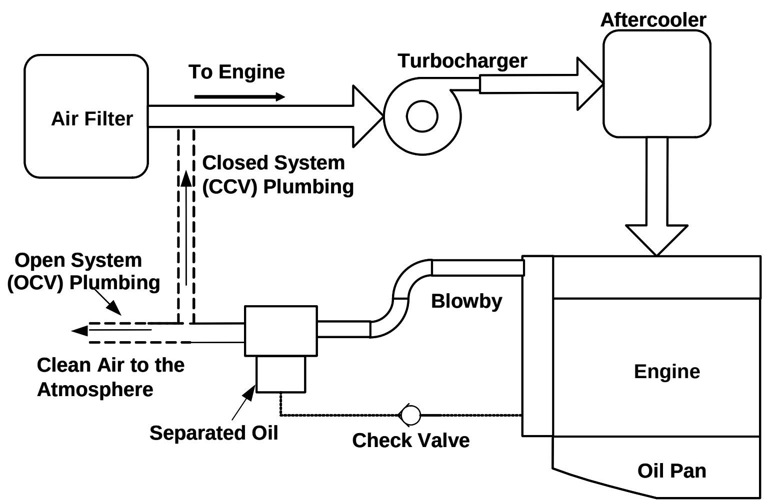

Fig. 4. Schematic diagram of open and closed crankcase ventilation system

In the CCV system, the filtered output is released into the engine intake. Because of incomplete combustion of the oil, higher particle and HC emissions can be experienced. This can reduce catalytic converter life and form deposits in the manifold, which will reduce heat transfer [Krause, et al., 1995]. A maximum mass concentration of 0.7 g/bhp-h is usually assumed for the design of a separation/filtration system for crankcase ventilation. In other words, the mass of blow-by particles is in the range of 1 – 20 g/h. In order to increase turbocharger durability, a high efficiency filter-coalescer with an efficiency of more than 90% for 1 micron and larger particles should be used.

Particles that pass through the compressor may deposit in aftercooler's passages. The oil film build-up on the aftercooler's walls has a negative effect on heat transfer rate thereby decreasing engine power.

4. Regulations and Requirements

Crankcase ventilation emissions are not specifically regulated, but are included as part of the total particulate emission from an engine. Society does not accept oil on road/parking lot/driveways, nor are oil droplets accepted on agricultural or mined goods, walls in the case of stationary engines, generator room/switchgear/controls, etc. The EPA 2007 total engine emission regulations that affect specifications for crankcase ventilation systems establish the concentration level at 0.01g/hp*hr of particulate matter.

In a CCV system, the blowby is usually released to the engine air intake system between the filter and turbocharger. Engine producers specify the minimum filter efficiency that guarantees long life of the turbocharger. Figure 5 shows turbocharger efficiency for a ventilation system with and without a filter. The build up of coked material in the diffuser section causes a decrease in turbocharger efficiency.

Table 1 [Pardue, 2004] provides data on the engine crankcase contribution to the total emission. Three types of engines were tested without filtration systems and with filters having 97% and 90% efficiency. The US 2007 PM specification was used to calculate the percentage of the total allowed emission of particulate matter. For engines with no filters, the crankcase emission itself is higher than the total permissible engine emission. When a 90% filter is used, blowby may represent 5 to 10 % of total particulate matter limits. A 97% or more efficient filter could possibly be used in an open system.

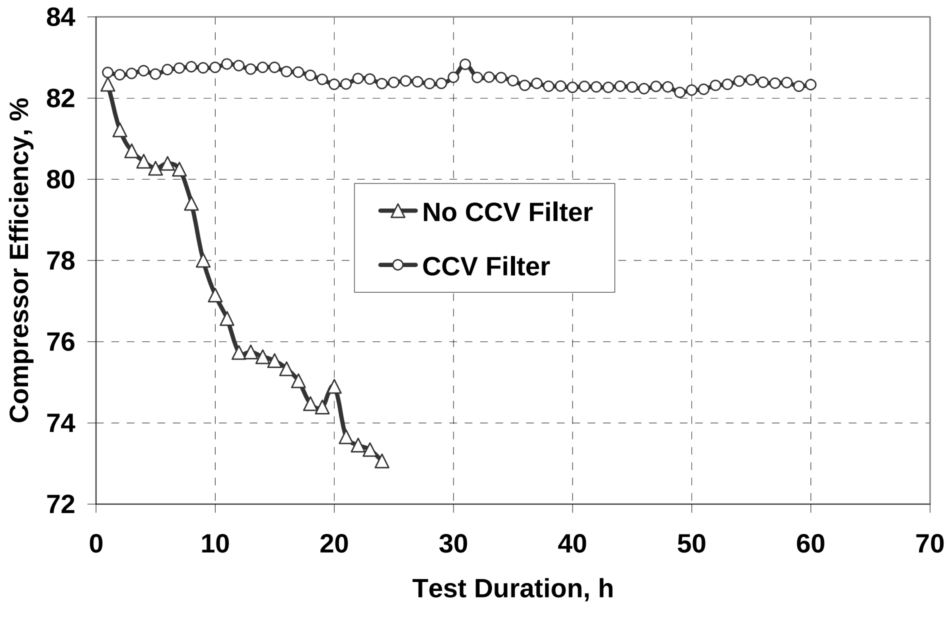

Fig. 5. Turbocharger degradation caused by crankcase contaminants

Tab. 1. Percentage of US 2007 allowable particulate matter emissions

Engine	if 97 % efficient	if 90 % efficient	no filter
A	1.2 %	4.2 %	41- 42 %
B	3 %	10 %	85 – 120 %
C	1.5 %	5 %	42 – 59 %

5. Test Methods

The SAE J2500 standard was developed to address on-engine and off-engine Crankcase Ventilation testing. The standard was replaced by ISO standard development in 2001.

In March 2001, a decision was made to split the standard into two parts, lab and engine testing. The lab testing section will only address clean oil at this time. The ISO standard drafts were called ISO/ CD 20654-1: Road Vehicles: Aerosol separator performance test for diesel and petrol engines – Part 1: Laboratory test method and ISO/ CD 20654-2: Road Vehicles: Aerosol separator performance test for diesel and petrol engines – Part 2. The engine testing section is not clearly defined at this time. In fact, ISO has recently decided to start over with the development of this standard.

6. Advanced Coalescer and Its Performance

Coalescing filtration in an engine crankcase ventilation system is complex because of the nature of the contaminants generated in the engine. Oil mist and vapor, fuel mist and vapor, combustion by-products, wear particles, and contaminants that penetrate the air intake system are the major constituents.

The term "coalescing filtration" was introduced approximately 20 years ago. Now, this term is commonly used in academia and industry [Chokdeepanich and Chase, 2000]. Coalescing filtration includes classical particle filtration mechanisms, coalescing processes on filter media surfaces and in the internal space of porous or fibrous media, as well as the liquid saturation stage and liquid release (drainage). It is understood that in coalescing filtration the incoming droplets are slowed or captured by the fibers in the filter. The droplets collide with each other or with droplets on the fibers and merge (coalesce). The enlarged drops migrate through the medium and drain.

A classical filter-coalescer shown in Figure 6 [US. patent 4,878,929] is composed of several layers of different fibrous material. The role of each layer is precisely determined. For instance, the second layer in the pleated material that is supported by the outer screen, is a coalescer that captures mist, the mist coalesces on fibers forming larger droplets that are discharged downwardly through the disloader section composed of resin-coated filters that facilitate the downward flow to prevent clogging of the media. A space between the first arrangement of media layers and the second stage made of fine fibers - fiberglass, for instance - is used for increased oil drainage needed at high oil mist concentration. The influent coalescing media are pleated to obtain low media velocity. At low velocity both the collection efficiency due to Brownian dynamics and coalescing efficiency due to long dwell time are high. Long dwell time affects the size of coalesced droplets. Large droplets will be separated by gravity and will eventually be returned to the engine crankcase.

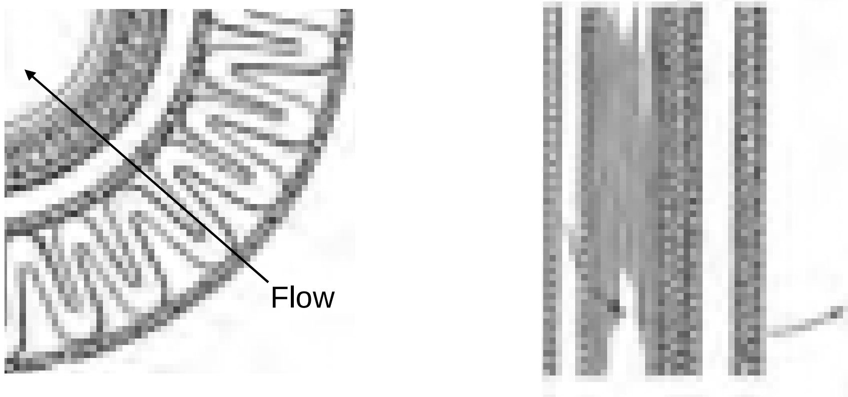

Fig. 6. Multilayer filter-coalescer

When the velocity is high (e.g., it the filter is too small for the specified flow rate), small and large droplets from oil-phobic fibers can be blown off resulting in decreased total filter efficiency similar to the re-entrainment phenomena of solid particles [Jaroszczyk et al., 1993]. However, the intensity of liquid droplets reentrainment is different than the reentrainment of aggregates of solid particles because of the capillary action between the liquid and neighboring fibers. Droplets are held in semi-capillaries formed by the fibers. Eventually, the coalesced droplets will move downward due to gravity and low adhesive forces between the oilphobic fibers and the droplets. However, the intensity of this gravity separation process weakens in oil-wetted fibers, which leads to more rapid media saturation. A typical pressure drop characteristic is shown in Figure 7. The coalescer’s efficiency may decrease if the outer layers of fibers do not collect the reentrained droplets.

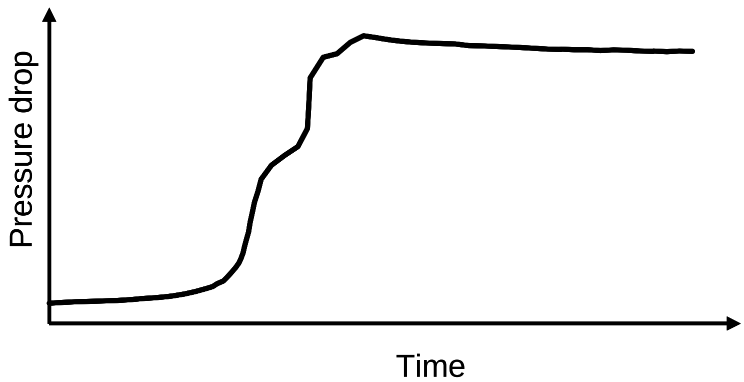

Fig. 7. Schematic diagram of coalescing process

The coalescing process starts when the first droplets are captured by fibers. The process continues until viscous drag forces surpass the adhesive forces. Because of the dynamic balance existing between the droplet collection, coalescing and reentrainment processes, various fiber diameters and porosity are used from the influent side to the effluent to optimize the efficiency for a specified pressure drop. In fact, our advanced coalescer is composed of hundreds of layers of fibers with different diameters that enable obtaining desired porosities. The outer layer should promote droplet drainage. In conclusion, fiber diameter, porosity, media thickness, and fiber properties are the major structural properties of a filter-coalescer.

Oil mist particles fed to the filter-coalescer may penetrate it in the form of mist, stay inside as liquid due to capillary forces, flow downward due to gravity, in both cases after coalescing, or reentrain due to aerodynamic drag forces. As in solid particle filtration, residual contaminant deposited remains in the filter due to adhesive forces in the solid particle filtration, and due to adhesive and capillary forces, in the of liquid particles filtration. The residual contaminant affects pressure drop by decreasing media porosity. Its value should be determined when designing a coalescer. The liquid residual saturation, S_r, is a function of the capillary number, N_{cap}, defined as [Brownell and Katz, 1947]:

$$S_r = \frac{1}{W} N_{cap}^{-0.264}, \qquad (1)$$

$$N_{cap} = \frac{K \Delta p_w}{h \tau \cos\theta}, \qquad (2)$$

where: W = coefficient that depends on media thickness, K = permeability of dry medium Δp_w = pressure drop across the wetted media, h = media thickness, τ = liquid surface tension, θ = liquid/fiber surface contact angle.

For media with a thickness of less than 5 cm, W = 40. For thinner media, a different equation can be used [Wakeman and Rushton, 1977; Wakeman, 1979].

$$S_r = 0.155\left[1 + 0.031\left(\frac{N_{cap}}{36K_1}\right)^{-0.49}\right], \qquad (3)$$

where K_1 = Kozeny constant. Values of the Kozeny constant K_1 given by Langmuir are in the range of 3.1 – 19.2 for packing density ranging from 0.9 to 0.01 [Langmuir, 1942].

Davies equation is commonly used to calculate pressure drop of fibrous media [Davies, 1952].

$$\Delta P = \frac{64\mu \cdot Q \cdot h \cdot \alpha^{1.5} \cdot (1 + 56\alpha^3)}{4A \cdot R_f^{\ 2}}, \qquad (4)$$

where: μ = gas viscosity, Q = volumetric flow rate, h = media thickness, α = packing density, A = media area exposed to flow, R_f = fiber radius.

This model was developed for $\alpha < 0.02$ and for Reynolds numbers >1. The equation was verified in series of experiments. When pressure drop was calculated and compared with experiments, it gives results from 80 to 170% of the experimental values [Liew and Conder, 1985].

Because of relatively broad particle size distribution and flow parameters, three-filtration mechanisms Brownian diffusion, interception, and inertial impaction should be considered when designing a filter-coalescer for engine crankcase ventilation system. Friedlander [Friedlander, 1957; Friedlander, 1958] combined all of them in one simple equation:

$$E_c \cdot N_R \cdot P_e = 6\left(N_R \cdot P_e^{1/3} \cdot R_e^{\ 1/6}\right) + 3\left(N_R \cdot P_e^{1/3} \cdot R_e^{\ 1/6}\right)^3, \qquad (5)$$

where: $N_R = \frac{d_p}{d_f}$ = interception parameter (particle diameter/fiber diameter), $Pe = \frac{d_f \cdot v}{Dif}$ = Peclet number, $D_{iif} = \frac{CkT}{3\pi\mu_a d_p}$ = diffusivity, C = Cunningham correction factor, k = Boltzmann's constant, μ_a = gas viscosity, T = temperature [°K], $\mathrm{Re} = \frac{\rho_a v d_f}{\mu} = \frac{v d_f}{\nu}$ = Reynolds number, ρ_a = gas density, v = gas velocity, υ = gas kinematic viscosity.

For the same filtration mechanisms, Davies [Davies, 1952] gives an equation:

$$E_c = 0.16\left[N_R + (0.5 + 0.8N_R)\cdot\left(Pe^{-1} + Stk\right) - 0.105\cdot N_R\left(Pe^{-1} + Stk\right)^2\right], \quad (6)$$

where the Stokes Number is $S_{tk} = \frac{C\cdot\rho_p\cdot d_p{}^2\cdot v_p{}^2}{18\cdot\mu_a\cdot d_f}$; v_p = particle density.

In all these equations, the influence of neighboring fibers is not considered. Moreover, the assumption was that the adhesive forces have unlimited value (nor bouncing of particles).

Total filter efficiency is calculated from a general equation that combines all important filtration mechanisms:

$$E_{filter} = 1 - \exp\left[\frac{-4E_i\cdot\alpha\cdot v\cdot h}{\pi\cdot(1-\alpha)\cdot d_f}\right], \quad (7)$$

where E_i is efficiency for an individual mechanism, v = velocity, and d_f = fiber diameter.
Total efficiency E for multilayer filer media is calculated from equation:

$$E = 1 - \prod_{l=1}^{n}\left(1 - E_l\right), \quad (8)$$

Here, E_l = efficiency for each layer.

Efficiency for each filtration mechanism can be calculated from numerous equations [Pich, 1987, Brown, 1993, Davies, 1966, Davies, 1973, Dorman, 1974, Flagan, 1988, Friedlander, 1977, 1964, Green, and Lane,1964, Löffler, 1971]. The selection of a particular equation requires detailed information on flow conditions of the filter-coalescer, its physical structure, and importantly, assumptions and boundary conditions of the mathematical model.

Particles in the range of 0.001-0.2 microns follow random Brownian motion in the air stream. Media thickness is important here since the residence time increases or thick media. Particles 2 micron and larger are removed by direct impact. Particles in the range of 0.2-2 microns are the most difficult to remove. Because of their low mass, they generally follow the stream line around the fiber and pass through the filter uncollected. This is the situation experienced in fine oil mist filtration.

We selected depth-type synthetic media manufactured using a technology that enables achieving gradient porosity and a wide range of fiber diameter. This technology provides flexibility of obtaining fiber diameter from submicron size to coarse fibers and porosities that allow high collection and coalescing efficiency, low restriction, and extended product life. We selected temperature and chemically resistant materials with long life in hot oil environments. Figure 8 shows one of many available shapes of the filter-coalescer. The Figure also shows a section of used media taken from a filter that was in operation on an engine. Layers of fibers were separated in the laboratory for detail stud. The Fractional efficiency of the new coalescer is shown in Figure 9. The size and shape can be modified to meet engine producer specification and space requirements. Fiber size and porosity gradient throughout the media were calculated for enhanced collection and coalescing properties. We use both very fine fibers to achieve high efficiency and large fibers to obtain high media structural stability and oil drainage.

Fig. 8. New filter coalescer – two left photos, and a section of a coalescer taken for lab inspection after long operation on an engine (layers of fibers separated in the laboratory for detail study) – right photo

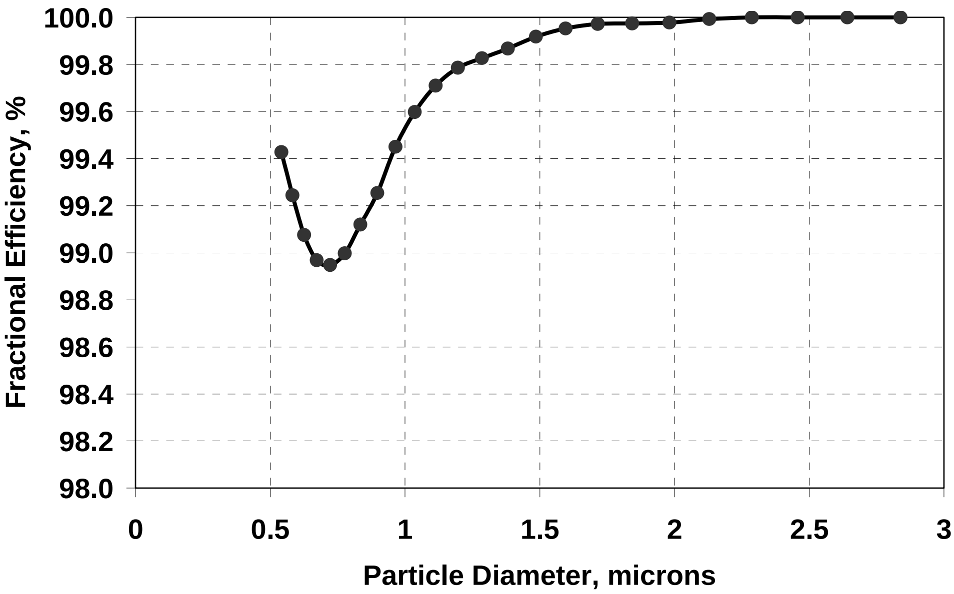

Fig. 9. Fractional efficiency of high efficiency coalescer shown in Figure 8

7. Historical Trend in Separation and Filtration Solution to Engine Crankcase Emission

Figure 10 shows the development of separation/filtration technology. Historically, mesh, foam, labyrinth, depth-type cotton-cellulose media, fiberglass, synthetic, depth and pleated media, cyclones, impactors, centrifuges, and electrostatic precipitators have been tried in engine crankcase ventilation systems.

Labyrinth, cyclones, impactors, and centrifuges utilize particle inertia that is a function of fluid and particle density. In the case of solid mineral particles, the density difference between air and ISO fine dust, for instance, is 1:2200. Therefore, removal efficiency for solid particles in these types of separators is high. In the case of oil particles, the ratio is 1:700. On the one hand, solid particles may easily bounce and reentrain, especially at high velocities, while liquid particles remain on collecting surfaces. Separators require high velocities to achieve high efficiency. This is not the case in crankcase ventilation. The only separators that may achieve high efficiency are impactors where particles are accelerated in nozzles or centrifuges. Therefore, filtration and electrical precipitation remain the only methods that can deliver high efficiency at low aerosol velocity.

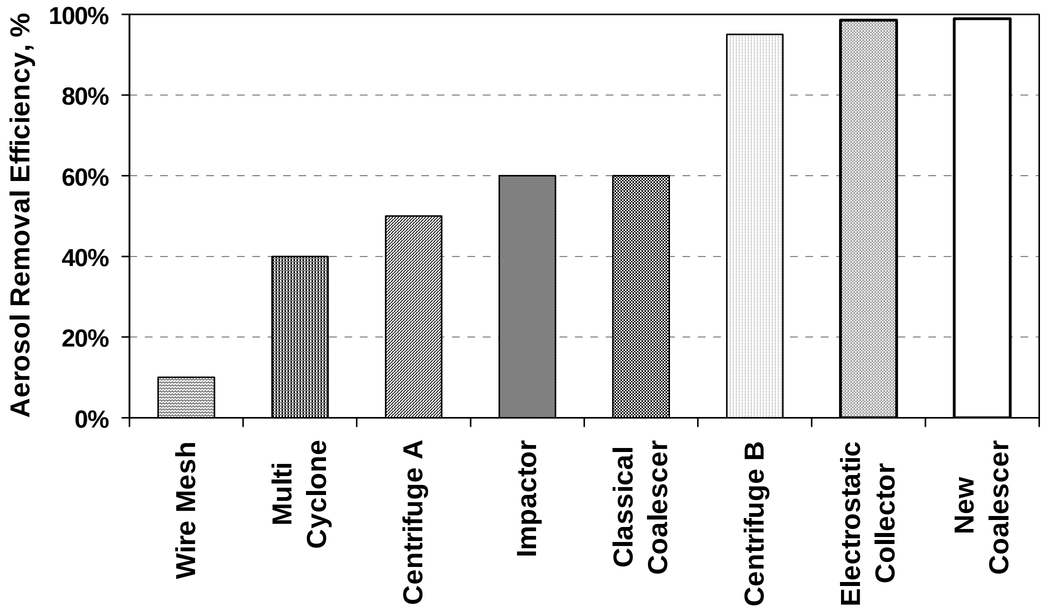

Fig. 10. Historical trend in separation/filtration systems development for crankcase ventilation systems

In the case of oil mist injected into the exhaust system, most hydrocarbons will burn off. However, the oil is lost, and emissions and engine backpressure are increased.

High filtration efficiency is necessary in the OCV system to minimize total engine emission and the impact on the environment. Particulate emission from CV system without any filter can be as high as 120% of the total engine emission allowed by the US 2007 Regulations [Heckel, et al., 2006, Pardue, 2004]. High efficiency coalescers typically need to accommodate fine fibers which usually results in high pressure drop. Because of the unacceptable pressure drop, efficiency of approximately 70% was acceptable years ago. Due to new developments in coalescer technology, pressure drop of new high efficiency media is acceptable; therefore, the efficiency target is now in the range of 90 – 99%.

A similar efficiency level may be required for CCV systems used on high boost pressure turbochargers; however, some turbochargers can tolerate a contaminant load as high as 2-3 g/h [Banerjee, et al., 2006]. In the case of a high mass load of oil mist and droplets, a two-stage filter-separator is necessary to achieve long life of the filtration system. The separator section removes oil droplets and larger particles preventing the coalescer from clogging.

8. Conclusions

- Engine crankcase separators and coalescers operate at variable flow rates and in complex environmental conditions. The contaminants are composed of liquid mist, oil droplets, and solid particles. They are usually fine particles with sizes below 5 microns, many in the range of the most penetrating particles. Therefore, is extremely difficult to design a filtration system that can meet new emission regulations.
- High filtration efficiency is necessary in the OCV system to minimize total engine emission and the impact on the environment.
- Only high efficiency filtration systems with efficiency more than 90-99% for 1 micron and larger particles can efficiently protect high boost pressure turbochargers.

- A new coalescer has been developed with efficiency approaching 99% for the most penetrating particles. It can be used separately or combined with an impactor for extreme crankcase engine environment.

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