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A Sure Way to Cut Emissions from In-Use Diesel Vehicles - A Retrofit System from Donaldson

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DIESEL EMISSIONS TODAY

Diesel engines are widely used today in transportation vehicles due to their superior energy efficiency. Offering the best fuel economy among all existing power sources, diesel engines serve as an effective means to curtail global warming by producing the least amount of greenhouse gases. However, diesel engines are a significant source of particulate matter (PM). Diesel engines also emit gaseous pollutants such as nitrogen oxides (NOx), unburned hydrocarbons (HC) and carbon monoxide (CO). These hazardous pollutants are of particular concern in urban areas where diesel engines are abundant.

Legislative regulations on diesel emissions have been and continue to be increasingly stringent. On the U.S. federal level, new limits on PM and NOx have been proposed for 2007 by the EPA, calling for at least a 90% reduction in both from their current levels. In the mean time, however, the diesel engines currently on the road pollute at much higher rates. There are about 1.2 million existing diesel engines in the state of California alone. These vehicles currently emit 26,000 tons of diesel PM per year[1].

Diesel engines can run for more than 1,000,000 miles and last for 20 to 30 years[2]. To accelerate the pollution reduction, the EPA has implemented a Voluntary Diesel Retrofit Program to reduce emissions from in-use diesel vehicles. In California, reducing emissions from existing diesel vehicles will be mandatory. Diesel fleet owners will be required to either install retrofit systems that have been approved by California Air Resources Board (CARB), or replace engines, or use alternative fuels.

RETROFIT TECHNOLOGIES

Several retrofit technologies for PM reduction are being developed to make existing diesel engines cleaner. There are pros and cons about each technology. Two of the primary retrofit options are Diesel Particulate Filters (DPF) and Diesel Oxidation Catalysts (DOC).

A DPF collects the particulate matter from the engine exhaust efficiently but requires a means to remove the accumulated PM. This process is known as regeneration of the DPF. An active regeneration method utilizes a heat-generating device such as an electric heater or a fuel burner to burn off the soot. Active systems have a tendency to become complex. A passive regeneration (no active heat input) DPF relies on catalytic reactions to oxidize the soot on a continuous basis. Passive systems have rather demanding requirements on engine exhaust temperature and fuel properties for the catalyst to work satisfactorily. For example, there are two passive DPF systems verified by CARB for retrofitting in-use diesel engines in California, both requiring the exhaust gas temperature to be higher than a minimum level for a significant period of time and the sulfur content in fuel to not exceed 15 ppm. As a result, the systems can only be applied to a limited number of diesel engines of specified model years[3].

A DOC is a passive device that converts, through catalytic reactions, the soluble organic fraction (SOF) in the PM into non-pollutants. The SOF is a precursor of the ultrafine nanoparticles and a source of carcinogen and diesel odor. SOF content in the total PM is typically in the range of 20–40 percent, depending upon the engine and its operating conditions. The reduction of PM by the use of DOC technology is typically in the range of 10–30 percent. One challenge facing DOC technology is how to ensure the DOC does not produce too much sulfate, a typical byproduct and a form of particulate matter.

THE DONALDSON SYSTEM

Engineers at Donaldson Company, Inc. in Minneapolis, Minnesota, recently developed a diesel retrofit system that combines a DOC muffler with a new closed crankcase filtration system (Spiracle™). Spiracle is designed to significantly reduce crankcase vent emissions (blow-by) from the engine. This combination system was recently verified by CARB for Level I PM reduction (greater than 25%).

The Donaldson system also provides significant reduction in gaseous pollutants (HC and CO). Table 1 lists individual emission reductions by the Donaldson retrofit system. The reductions were achieved over the U.S. Federal Test Procedure (FTP) heavy-duty transient cycle. Upon installation, the system can provide immediate emission reductions for almost every major engine family produced in 1991 or after[3]. Depending on the catalyst formulation chosen, the fuel sulfur content can be as high as 500 ppm.

The Donaldson retrofit system with its proven DOC muffler technology (over 500,000 units in service since the mid 90's) provides a cost-effective solution to cut emissions from in-use diesel engines. More widely applicable than a DPF, it is also far less costly. Greater durability and less maintenance are assured since the flow-through DOC reduces the potential for plugging due to soot accumulation. The well-engineered oxidation catalyst is a proven technology in both the automotive and diesel industries.

Table 1. Diesel emission reductions by the Donaldson retrofit system over the FTP heavy-duty transient cycle

Emission	Reduction
PM	25-50%
NOx	0%
HC	50-85%
CO	25-50%
Blow-by	100%

REDUCTION IN TAILPIPE EMISSIONS

Typical compositions of diesel particulate matter are illustrated in Figure 1. The largest component of PM is carbon (black soot). The second significant component is condensed unburned hydrocarbons, usually termed as SOF. The third component is sulfate, which is formed by combustion of the sulfur contained in the fuel. The remainder is comprised of trace amount of ashes, etc. The Donaldson DOC muffler assembly, shown in
Figure 2, is primarily effective in removing the SOF component of diesel PM.

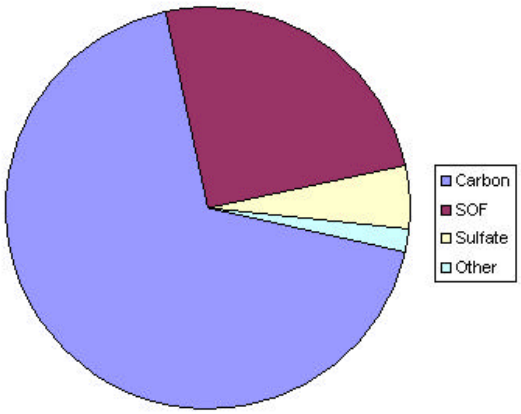

Figure 1. Typical diesel PM compositions.

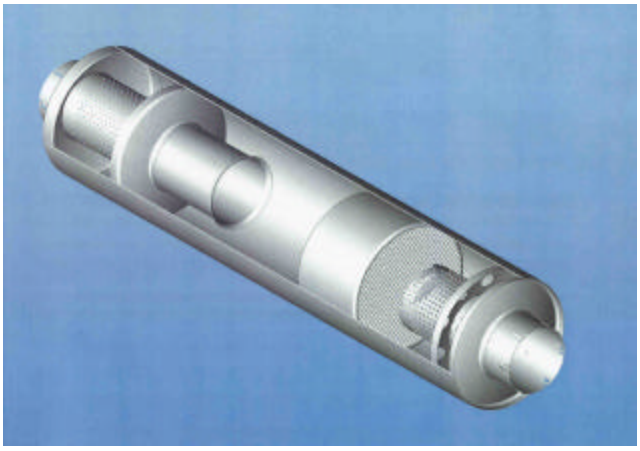

Figure 2. Illustration of the Donaldson DOC muffler.

Figure 3 shows typical mass and number-weighted size distributions of diesel exhaust particles[4]. Most of the particle mass exists in the so-called Accumulation Mode in the 0.1-1.0 μm diameter range. However, on a number basis, an overwhelmingly large number of particles are concentrated in the Nuclei Mode, which is in the 0.005-0.05 μm (or 5-50 nm) diameter range. Particles in this size range are commonly referred to as nanoparticles.

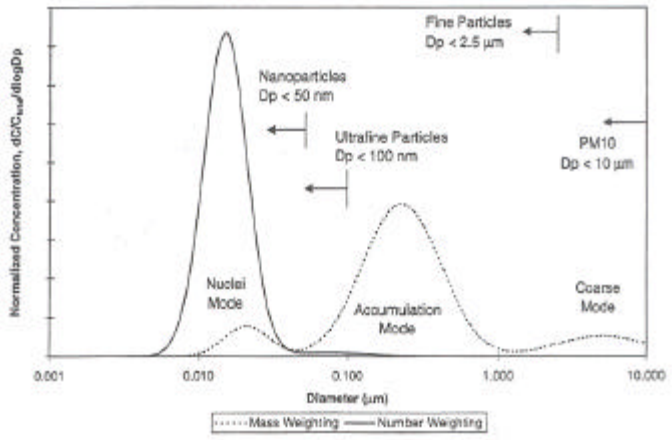

Figure 3. Typical mass and number weighted size distributions of diesel PM[4].

The nanoparticles in diesel exhaust typically account for up to 20% of the particle mass but more than 90% of the particle number. There have been various reports on the adverse health effects caused by nanoparticles[5,6,7,8]. Scientists have also suggested that nanoparticles are more harmful than larger particles[8].

Research results suggest that, while the Accumulation Mode is where the larger carbonaceous agglomerates reside, the Nuclei Mode usually consists of volatile organic and sulfuric compounds. A DPF is most effective at removing the larger Accumulation Mode particles, while a DOC mainly removes the organic compounds (unburned hydrocarbons) or SOF and nanoparticles that form later in the exhaust stage[4]. Therefore, while removing approximately 25% of PM mass, a DOC has the potential to remove more than 90% of the total particles by number.

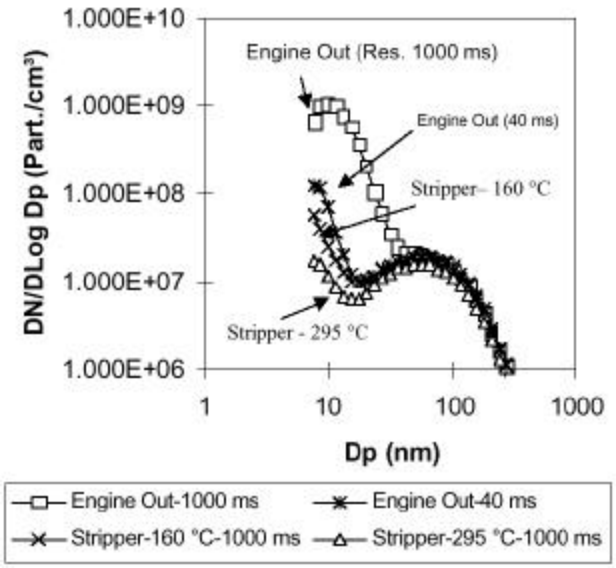

Figure 4. Particle size distributions from a turbo-charged diesel engine with and without a catalyst[9]. Reprinted with permission from SAE 982599 © 1998 SAE International

Figure 4 shows the effectiveness of an oxidation catalyst in reducing nanoparticles from a diesel engine[9]. The catalyst used here is essentially a small size DOC catalyst, called a catalyst stripper. Like a DOC, a catalytic stripper removes primarily the volatile SOF in the exhaust. In the figure, the horizontal coordinate represents particle diameter in µm, while the vertical coordinate represents the particle number density over a size increment on a log-scale. As shown, a stripper operated at 295°C and 1000ms residence time reduces the particle number density at 10 µm size by almost 99%! Therefore, a DOC system such as the Donaldson system should particularly improve the pollution situation in urban areas.

It should be noted that a DOC system can increase sulfate, another form of diesel PM (Figure 1). At higher exhaust temperatures the catalyst can promote the formation of sulfate. One remedy to this is to use Vanadium as a suppressant. At Donaldson, very careful and elaborate engineering was done to develop a catalyst formulation where optimal precious-metal-to-Vanadium ratio is achieved. As a result, the Donaldson retrofit system produces little to no sulfate increase.

REDUCTION OF BLOW-BY GAS EMISSIONS

In the U.S., the regulatory attention on diesel emissions has been primarily given to those coming from engine tailpipes. But another source of emissions is from a diesel engine's crankcase breather. The emitted blow-by aerosol consists mainly of oil droplets, with some carbon and traces of wear debris and dust[10]. Particle sizes range from 0.03 to 6 µm, which means that the aerosol is highly respirable. Figure 5 indicates blow-by gas emissions can be as much as 25% of the total emissions (tailpipe + blow-by) over an FTP transient cycle. In addition to aerosol emissions, engine blow-by is also a source of undesirable odors, fumes, engine compartment oil filming, and roadway/garage/parking
lot drips.

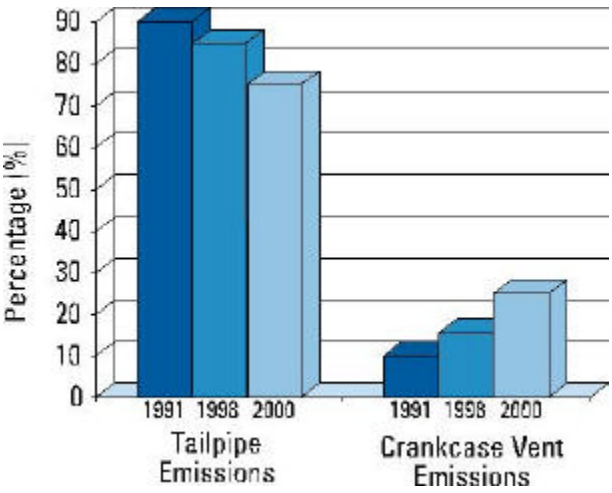

Figure 5. Diesel engine tailpipe and blow-by emissions over engine model year over an FTP transient cycle.

Blow-by emissions from in-use diesel engines are of concern today. The CARB approved Donaldson retrofit system includes a closed crankcase filtration system (Spiracle) designed to trap emissions carried in the blow-by gas. Figure 6 shows a schematic of the Spiracle system installed on a diesel engine. The EPA has proposed mandating closed crankcase engine operation for 2007 and beyond.

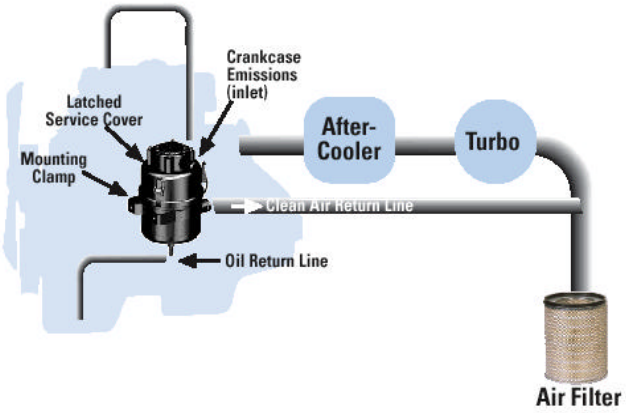

Figure 6. Schematic flowchart of the Spiracle™ system integrated in a diesel engine.

Figure 7 shows particle mass concentrations before and after the Spiracle system and the corresponding trapping efficiency versus particle size[11]. The results were obtained from blow-by gas on a DDC Series 60 engine at idle conditions. The Spiracle system can remove more than 90% of particle mass across the whole size range. The filtered gas downstream of the Spiracle is looped back to the engine intake, significantly reducing emissions from the crankcase breather to the atmosphere.

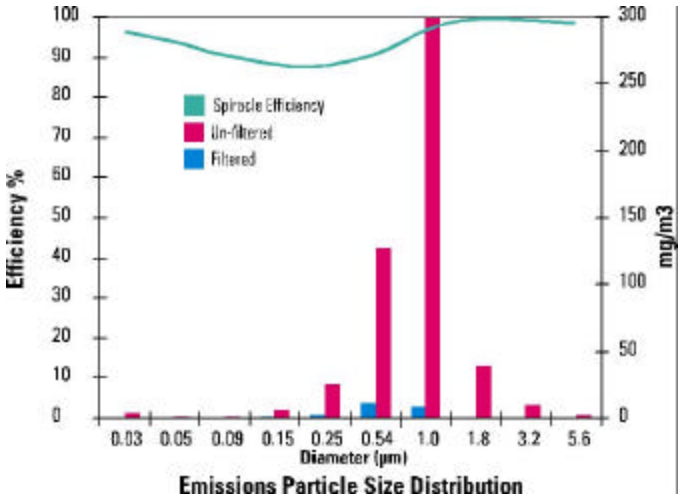

Figure 7. Particle mass concentrations before and after the Spiracle system and trapping efficiency over particle size. Results obtained from a DDC Series 60 diesel engine at idle conditions.

SUMMARY

A unique retrofit system combining a DOC Muffler with a Spiracle closed crankcase filtration system has been shown to be highly effective in reducing harmful tailpipe and crankcase emissions. The use of DOC technologies is cost effective and durable. The DOC muffler has the potential to remove over 90% of the harmful nanoparticles. It also significantly reduces gaseous pollutants as well as the characteristic diesel odor. The Spiracle closed crankcase filtration system significantly reduces the engine blow-by emissions, another significant source of pollution.

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