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ScienceDirect
Aerosol Science 37 (2006) 1140–1151
Journal of Aerosol Science
www.elsevier.com/locate/jaerosci

On-road evaluation of two Diesel exhaust aftertreatment devices

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Received 25 May 2005; received in revised form 7 November 2005; accepted 8 November 2005

Abstract

Two Diesel particulate matter emission control devices; the continuously regenerating trap (CRT^{TM}) and the catalyzed continuously regenerating trap (CCRT^{TM}) were evaluated using a mobile emissions laboratory. The source of emissions was the lab's engine that was fueled with 15 ppm sulfur fuel, and specially formulated, low sulfur (1300 ppm) lubrication oil. The objective was to characterize performance using real-time aerosol instrumentation, real-world dilution, and on-road driving conditions.

The devices when combined with low S fuel and lube oil effectively removed Diesel particulate matter. The CRT produced large quantities of nuclei mode particles, the quantity of which increased as a function of exhaust temperature. The CCRT reduced the exhaust particle number concentration to levels not detectable above background storage sites, thus eliminating precursors that form nuclei mode particles. Use of low S fuel and lubrication oil prolongs the storage process. Over time it is expected that this material would be released.

Keywords: Diesel; Nanoparticles; Nuclei mode; Continuously regenerating trap; Engine exhaust particle sizer; Exhaust aftertreatment; On-road measurements

1. Introduction

Particle emissions from internal combustion engines have traditionally been regulated solely on the basis of total particulate matter mass. Particle number emissions remain unregulated, and there is only a weak correlation between particle number and mass concentration (Hall et al., 2001). Engine exhaust aerosol size distributions are generally composed of three distinct modes nucleation, accumulation and coarse modes. For Diesel exhaust, nuclei-mode particles typically range in diameter from 3 to 30 nm, and are composed primarily of volatile organic and sulfur compounds. The accumulation mode contains most of the mass and ranges in size from 30 to 500 nm. It is composed primarily

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doi:10.1016/j.jaerosci.2005.11.003

of carbonaceous agglomerates and adsorbed material. The coarse mode consists of particles larger than 500 nm and contains 5–20% of the mass. These relatively large particles are formed by reentrainment of particular matter, which has been deposited on cylinder and exhaust system surfaces. All three modes are better defined by their discrete nature than by rigid size boundaries (Kittelson, 1998).

The particle size and concentration of volatile material emitted by Diesel engines are strongly dependent upon dilution and sampling conditions. Sulfur and organic compounds are generally found in the vapor phase in the tailpipe, and undergo gas-to-particle conversion during dilution and cooling. The gas-to-particle conversion processes, nucleation, condensation, and adsorption, are highly nonlinear and extremely sensitive to prevailing conditions. This is especially true for nucleation.

Carbonaceous soot particles are formed very early in the combustion process and most are oxidized at very high temperatures. Lubricating oil from cylinder walls is entrained and partially burned, and is responsible for much of the organic carbon associated with Diesel exhaust particles. Metallic additives in the lube oil may be converted to gas phase compounds, and then undergo gas-to-particle conversion as the exhaust dilutes and cools (Abdul-Khalek, Kittelson, Graskow, Wei, & Brear, 1998). Most of this material ends up as ash associated with accumulation mode particles, but ash nuclei may form if the ratio of metal to carbon particles is sufficiently high (Du, Kracklauer, & Kittelson, 1998; Kittelson, Dolan, Diver, & Aufderheide, 1978; Mayer et al., 1998). In most cases, on a mass basis, particles present in the tailpipe are found in the accumulation mode. As exhaust mixes with ambient air, volatile particle precursors, mainly sulfuric acid and hydrocarbons, become supersaturated and undergo gas-to-particle conversion to form volatile particles in the nuclei mode. Although the relative size of the nucleation and accumulation modes varies greatly by engine type, on-road measurements indicate most of the number concentration is found in the nuclei mode (Kittelson, Watts, & Johnson, 2002, 2004; Kittelson et al., 2003). Since nuclei mode particles are not present in the tailpipe, dilution conditions such as temperature and dilution rate may change their number concentration by an order of magnitude or more. On the other hand, accumulation mode particles, composed primarily of carbonaceous agglomerates and ash, are formed during combustion, and are less influenced by the dilution conditions. The presence of a large accumulation mode will act to suppress the formation of the nuclei mode because the carbonaceous agglomerates scavenge volatile material reducing the likelihood of gas-to-particle conversion (Khalek, Kittelson, & Brear, 2000).

EPA promulgated a lower particulate matter emission standard for Diesel engines, which takes effect in 2007. The new heavy-duty, on-road emission standard will be 0.0134 g/kwh. To meet this standard, Diesel engine manufacturers may have to use exhaust aftertreatment such as filtration devices that effectively remove nearly all of the carbonaceous agglomerates found in the accumulation mode. However, some of these filtration devices employ catalysts, which can cause an increase in sulfate emissions by the conversion of SO_2 emitted in exhaust to SO_3 and H_2SO_4. Nearly all sulfate emissions are found in the nuclei mode. The durability of filtration devices is dramatically improved by the use of ultra-low sulfur fuel. Thus, to maximize the emission reduction EPA has also promulgated a regulation that reduces the fuel sulfur content from 500 to 15 ppm wt% sulfur to be implemented 1 July 2006 (US EPA, 2001).

The objective of our tests was to evaluate the performance of two types of filtration devices under real-world, on-road cruise conditions to determine the impact of the filtration devices on particulate matter emissions and in particular quantify the impact on nuclei mode particles using very fast response instruments. It has been shown previously (Kittelson et al., 2002) that it is difficult to consistently duplicate the formation of the nuclei mode portion of a measured on-road size distribution in the laboratory under all conditions. It is not possible to consistently simulate the unsteady engine operating conditions that are a part of on-road operation. Further, the nuclei mode, as discussed above, has a much greater sensitivity to engine and dilution conditions than accumulation mode particles. The nuclei mode also has a strong dependence on ambient conditions, especially ambient temperature, and in general there is a greater tendency to form nuclei mode particles under real-world conditions.

This paper describes a unique method developed to evaluate emission control devices while operated under real-world, on-road driving conditions. It presents results from on-road evaluations of two types of filtration devices; a continuously regenerating trap (CRT^{TM}) and a catalyzed continuously regenerating trap (CCRT^{TM}) (Allansson et al., 2002; Cooper & Thoss, 1989). A CRT consists of a Diesel oxidation catalyst (DOC) followed by an uncatalyzed filter. The CCRT uses the same DOC and a catalyzed filter. The evaluations were carried out with two CRTs or two CCRTs installed on the University's Mobile Emissions Laboratory (MEL) described in detail elsewhere (Kittelson et al., 2000), but briefly described below.

The MEL is hauled by a Volvo tractor powered by an emissions year 2000, 6 cylinder, 12 L engine rated at 287 kW at 1800 rpm, 1964 Nm with dual exhaust stacks, and a gross vehicle weight of about 20,000 kg. For this evaluation the