

Effect of Lubricant Oil Properties on the Performance of Gasoline Particulate Filter (GPF)

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ABSTRACT

Mobile source emissions standards are becoming more stringent and particulate emissions from gasoline direct injection (GDI) engines represent a particular challenge. Gasoline particulate filter (GPF) is deemed as one possible technical solution for particulate emissions reduction. In this work, a study was conducted on eight formulations of lubricants to determine their effect on GDI engine particulate emissions and GPF performance. Accelerated ash loading tests were conducted on a 2.4L GDI engine with engine oil injection in gasoline fuel by 2%. The matrix of eight formulations was designed with changing levels of sulfated ash (SASH) level, Zinc dialkyldithiophosphates (ZDDP) level and detergent type. Comprehensive evaluations of particulates included mass, number, size distribution, composition, morphology and soot oxidation properties. GPF performance was assessed through filtration efficiency, back pressure and morphology. It was determined that oil formulation affects the particulate emission characteristics and subsequent GPF performance.

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BACKGROUND

Gasoline direct injection (GDI) engines, which achieve better fuel economy with high power outputs, have significantly gained in popularity as a propulsion system for light-duty passenger vehicles, and this trend is expected to continue. However, as they emit significantly increased particulate matter (PM) mass and number (PN), compared to conventional spark ignition engines, vehicles with GDI engines are required to meet stringent PM emissions standards. Starting from Euro 6, particulate emission regulation has been implemented for GDI vehicles. As it moves to Euro 6c, equivalent requirement is put upon GDI vehicles as diesel passenger car equipped with DPF, that is 4.5 g/km for mass and 6×10^{11} #/km for PN under the new European Driving Cycle (NEDC) following the Particle Measurement Programme (PMP) procedures.[1] Future use of real world driving emissions (RDE) could increase the challenges to meet these regulations even more. In the US, although there is no PN regulation yet, a more stringent mass requirement has been set for both CARB LEVIII and US EPA Tier 3. In details, the PM mass limit is set as 3 mg/mile starting in 2017 and 1 mg/mile starting 2025.[2]

In order to meet the stringent requirements on particulate emissions, many potential technologies have been proposed and evaluated, both in-cylinder control and after-treatment. While fuel injection technologies have been advanced to decrease PM emissions from

GDI engines, gasoline particulate filter (GPF) is considered as an enabling and cost-effective technology to meet those stringent regulations.[3]-[6]

Unlike diesel particulate filter (DPF), limited work has been done to develop fundamental understanding on GPF and its operation within the vehicle system.[7] Further, the impact of fluid properties (fuel, lubricant and additives) on GPF performance is not well known. Therefore, many insights on DPF and three way catalyst (GPF) have been adopted for GPF work.[8] However, the differences in operating conditions between GPF and DPF dictate that additional considerations need to be taken into account for successful GPF application. Those differences are manifested in that GPF is generally exposed to higher exhaust temperature with stoichiometric air fuel ratio rather than lean environment. Unlike diesel engines, increased exhaust temperatures from GDI engines necessitate the development of high porosity filters to minimize back pressure for fuel savings. Furthermore, it is not expected to have active regeneration for GPF service life, which leaves passive regeneration as the only choice to remove soot.

It was known that ash alters DPF performance in terms of backpressure, pressure drop response, soot storage capacity, soot distribution, catalyst activity.[9] Because GDI engines produce much lower levels of PM than diesel engines, ash has been considered an even more important factor that can affect GPF system performance

during the vehicle service life.[10], [11], [12] Ash can be derived from various sources, including lubricant oil, engine wear particles and other secondary sources.[9], [13] Lambert et al. found out that approximately 50 wt% of the collected ash was non-lubricant derived in their work to understand ash accumulation in GPFs over significant mileage.[14] The results indicate that the exhaust gas backpressure did increase with mileage accumulation and ash loading, but did not lead to significant decrease in fuel economy. In the meanwhile, as the significant contributor of ash, lubricant additive has been investigated for its impact on ash formation and according influence on DPF/GPF performance. It was found that ash, taken from filters of 100,000 mile run vehicle, enhanced soot oxidation reactivity at simulated tight contact and loose contact conditions.[15] The impact of ash on backpressure has been studied by many researchers on GPF/DPF.[16] Researchers also found that an ash membrane can effectively prevent soot from entering into the porous network of the filter wall. This can contribute to the reduction of the overall pressure drop compare to the no-ash case.[17]

It has been a logical development to apply catalyzed GPF (c-GPF) for GDI engines since the optimized design and robust formulation can simultaneously reduce gaseous emissions while PM emissions are well controlled.[18] In order to ensure the satisfactory performance of c-GPF over full useful life (FUL), the interaction between lubricant-derived ash and c-GPF (both the catalyst washcoat and substrate) needs to be understood. This fundamental understanding will help for the c-GPF system development and lubricant formulation optimization. Early investigations show that the ratio of Ca to ZDDP is critical in the degree of deactivation: when the ratio is low, amorphous zinc-phosphate glasses and other zinc and/or phosphorus compounds deposited on the surface of catalyst washcoat reduce porosity of the coating.[19] Another study indicates that phosphorus, which has higher diffusion coefficients than zinc, calcium and magnesium, can penetrate deep into the washcoat, facilitating deactivation process.[20] As the deactivation of three-way catalyst (TWC) is obvious with the inclusion of P derived from engine oil, low volatility engine oils have been developed to reduce P impacts on catalysts.[21]-[22] The main concern for the impact of ash level is that the non-combustible ash deposits trapped in the channels of the filter may potentially increase backpressure over the filter and further affect its performance.[23] Earlier experience from DPF work indicates that detergents have significant contribution to the ash accumulation in the channel.[24] But the effect largely depends on the system design, detailed oil formulation and operating condition. Ito et al. reported that there is no interaction or phase change of ash components and cordierite material was observed during an extensive c-GPF field test up to 160,000 km. [18]

Generally, there is a trade-off relationship between backpressure, PN filtration efficiency, soot/ash loading.[25] Therefore, oil formulation as a whole shall be investigated in order to be compatible with GPF/DPF application while delivering desired performance to engine system operation. Here, an accelerated ash loading condition is achieved by direct engine oil injection into the combustion chamber.

The effects of the experimental oil formulation compositions on the GPF performance, chemistry, and composition of particulates produced are addressed.

EXPERIMENTAL

1. Experimental Setup

Engine Setup

A 2.4 L 4-cylinder, naturally aspirated, production GDI spark-ignition engine was used in this work. The engine geometry and specifications are given in Table 1. This engine is basically operated at homogenous and stoichiometric charge conditions. The engine was mounted on a 112 kW blower-cooled AC dynamometer for speed control and torque measurements. In this work, the certified Tier 2 EEE fuel and experimental style additive formulation in conventional motor oil with an SAE grade of 5W-20 were used.

Table 1. Engine geometry and specification

Parameter	Unit	Specification/Information
Displacement	L	2.4
Bore	mm	88
Stroke	mm	97
Induction		Natural aspirated
Injection		Multi-hole, side mounted, direct injection
EGR		No EGR
Compression ratio		11.3
Rated power	kW	147.8 kW @ 6300 rpm
Rated torque	Nm	250Nm @ 4250 rpm

GPF Test Setup and Procedure

A partial flow exhaust system was built to test prototype bench-scale GPFs (2" in diameter and 6" in length) at a wide range of flow rates (0 - 40 kg/hr) at the same steady state engine condition. Figure 1 (a) shows the schematics of the partial flow GPF setup. The flow rate to the GPF is controlled by two flow control valves at the main exhaust pipe and the partial flow exhaust pipe. The pressure drop and temperatures across the filter were measured, and the particulate number and mass filtration efficiencies were calculated by measuring the particulate number and mass of upstream and downstream of the filter. The compressed air and air heater (6 kW) were connected to the partial flow exhaust pipe at the GPF inlet, which allows cold air and hot air (max. 600°C @ filter inlet) test for pressure drop measurement and complete soot oxidation. Reproducibility of this technique has been checked and gives representative results. For accelerated ash loading, lube oil was sprayed into the fuel supply line at a controlled rate by using a solenoid valve in connection with a pulse generator to the lube oil in gasoline fuel by 2 wt. %, which allows about 1 g/L of ash loading in 1 hour at 1250 rpm - 25% load with 1 % sulfated ash lube oil.

The GPF test procedure was designed for efficient and fair comparison of GPF performance after ash loading, as shown in Figure 1 (b). Every new filter was pre-treated in hot air (550°C) before the test. Clean filter pressure drop (without soot) was first measured cold (room temperature) air, and the clean filtration efficiency was measured under steady state engine condition of 1250 rpm - 25% and flow rate of 15 kg/hr. Accelerated ash loading was conducted to target lube oil consumption, followed by complete soot oxidation with hot air (550°C). In the complete soot oxidation process, the hot air kept flowing at 20 kg/hr until the measured pressure drop change gets smaller than 0.05 kPa/10 min. The engine condition was maintained at 1250 rpm - 25% and fuel was doped by 2 wt. % in the accelerated ash loading. After ash loading, soot was completely oxidized with hot air (550°C) to measure clean filter pressure drop and filtration efficiency after ash loading. In this study this procedure was repeated twice for each lube oil sample, at target lube oil consumptions of 61 g and 122 g, and the pressure drop and filtration efficiency changes at earlier ash loading were compared for different lube oil additive formulation.

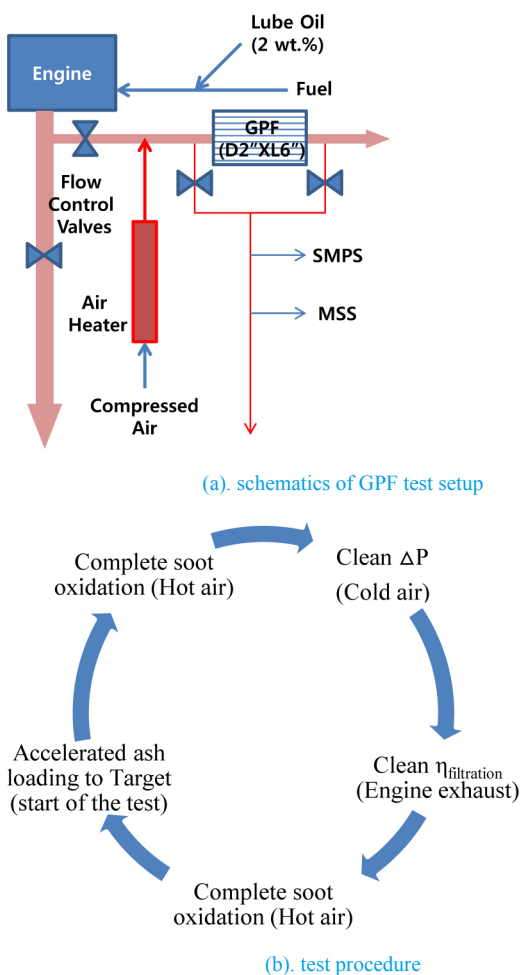


Figure 1. GPF test setup and procedure

2. Exhaust Emissions Measurements

Soot mass concentration was measured using a high-sensitivity photo-acoustic sensor (AVL 483 micro soot sensor). For partial flow measurements of particulate number and size distribution, a scanning mobility particle sizer (SMPS, TSI Model 3936) with a condensed particle counter (CPC, TSI Model 3022A) was used after exhaust emissions were diluted by a fine particle sampler (Dekati FPS-4000). The raw emissions were sampled from the exhaust pipe through the heated stainless steel probe and subsequently diluted in two stages, a perforated tube for the primary dilution and an ejector pump for the secondary dilution. The temperatures of the sampling probe, primary dilution air were controlled at 350°C in this study. The actual dilution ratio was calculated based on measuring the CO₂ concentrations before and after dilution using an infrared CO₂ analyzer (California Analytical Instruments, Inc., Model 200).

3. Characterization Tools

Thermogravimetric Analysis (TGA)

A TGA instrument (TA Instruments Q50) was used to evaluate volatile organic fraction (VOF) and oxidation reactivity of GDI PM collected on Teflon® filters. Each PM sample scraped from a filter was loaded in a platinum pan of 9.85 mm diameter and 1.68 mm height. Each sample of 1 - 1.5 mg was thermally treated under N₂ at 600°C for 100 minutes and then, isothermal oxidation was performed at the same temperature with 8% O₂ in N₂.

Transmission Electron Microscopy (TEM)

TEM analysis was performed to visually examine morphology and nanostructures of GDI particles. A TEM grid was exposed to an exhaust stream, so that hot particles in the exhaust transported onto the TEM grid by the temperature difference. Carbon-coated TEM grids were used for the morphological examination, while lacey carbon-coated TEM grids were for detailed nanostructures at relatively high magnifications. Each TEM grid was loaded in a single tilt holder and the TEM images were taken at an acceleration voltage of 200kV by a JEOL JEM-2200F electron microscope. The energy dispersive X-ray (EDX) spectra were investigated by an INCA X-ray microanalysis system equipped on the microscope. Particles were investigated in a magnification range of 20,000 to 600,000X.

4. Oil Matrix

Eight (8) fully formulated experimental engine oils of SAE 5W-20 viscosity grade were prepared according to the 3-factor, 2-level matrix design shown in Figure 2. The three factors are chemical properties of the engine oil: SASH, phosphorus level from ZDDP, and alkaline earth metal type from detergents. Treating levels of ZDDP and detergent for each matrix oil were varied accordingly in order to meet target SASH and P values. Other essential components, such as dispersant, antioxidant, friction modifier and viscosity modifier, were treated at constant levels for all oils. The base oils used in this work are of Group III base stock as categorized by API in API 1509 EOLCS Appendix E publication.