

Impact of High Sulfur Military JP-8 Fuel on Heavy Duty Diesel Engine EGR Cooler Condensate

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ABSTRACT

Low-sulfur "clean" diesel fuel has been mandated in the US and Europe. However, quality of diesel fuel, particularly the sulfur content, varies significantly in other parts of the world. Due to logistical issues in various theaters of operation, the Army is often forced to rely on local fuel supplies, which exposes vehicles to diesel fuel or jet fuel (JP-8) with elevated levels of sulfur. Modern engines typically use cooled Exhaust Gas Recirculation (EGR) to meet emissions regulations. Using high-sulfur fuels and cooled EGR elevates problems associated with cooler fouling and corrosion of engine components. Hence, an experimental study has been carried out in a heavy-duty diesel engine running on standard JP-8 fuel and fuel doped with 2870 ppm of sulfur. Gas was sampled from the EGR cooler and analyzed using a condensate collection device developed according to a modified ASTM 3226-73T standard. Engine-out emissions were analyzed in parallel. Analysis of results indicates significantly increased levels of sulfur-dioxide and particulate mass with high-sulfur fuel, but negligible amounts of condensed sulfuric acid under normal operating temperatures.

INTRODUCTION

For logistical reasons, the US military has initiated a *single fuel forward strategy* for its vehicle and aircraft fleets that are stationed and operated in many parts of the world [1]. Currently the single fuel forward is Jet Propellant type 8 (JP-8), a Jet A-1 kerosene-based fuel. When troops are deployed, the military often taps into local fuel supplies in various theaters of operation. In that case, fuel properties may vary through a very wide range. In particular, the sulfur content in some regions is unregulated and may reach extremely high values.

High sulfur content of 3000 ppm or more (on a mass basis) can have an impact on the durability of engine in-cylinder components, engine performance and particulate matter formation [1]. In addition, high sulfur

content affects engine durability due to corrosion caused by the exhaust gas condensate. The corrosion of the heat exchanger in the Exhaust Gas Recirculation (EGR) system is a particular concern on modern engines with EGR. Relatively high amounts of EGR are used for dilution and reduction of combustion temperatures, thus minimizing formation of nitric oxides. However, high mass flow rates of exhaust through the cooler and the presence of particulate matter (PM) in the exhaust lead to fouling of cooler interior walls. Presence of sulfates in soot particles or direct condensation of sulfuric acid has the potential to significantly magnify the corrosion and fouling problems. Sulfates that stick to particulates result from the increased concentrations of SO_2 and SO_3 gas, and sulfurous (H_2SO_3) and sulfuric acid (H_2SO_4). Hence, they are all highly corrosive and a likely reason for corrosion problems observed on some engines [2]. While previous work has identified the problem, additional insight is needed for generating a full understanding about the mechanisms and magnitude of corrosive effects.

Previous research has mostly focused on the effects of high-sulfur JP-8 on combustion and emissions. A JP-8 fuel with 0.2532%wt sulfur was used in a single-cylinder Petter engine by Korres et al. [1]. It was shown that JP-8 can match the performance of diesel by implementing an optimized engine calibration. Yost et al. [3] have shown that the PM-NOx tradeoff curve for JP-8 shifts favorably compared to diesel fuel for a 0-20% range of EGR, but PM emissions increased as sulfur content in the fuel increased. PM emissions have a great impact on exhaust gas visibility, which increases detectability and vulnerability of trucks and tanks on the battlefield.

The objective of this study is to examine the emissions and the composition of the condensate from the EGR cooler of the heavy-duty diesel engine operated with regular JP-8 containing 40 ppm of sulfur. These results were compared to those obtained with JP-8 having a 2870 ppm sulfur content. A special apparatus is designed to sample the exhaust from the EGR cooler,

and enable separation of solid particles and subsequent controlled condensation of the gas. The temperature control in the apparatus allows independent quantification of the sulfur-dioxide and sulfuric acid present in the exhaust gas. The engine is a Detroit Diesel Series 60, equipped with a variable geometry turbocharger (VGT) and EGR cooler typical of the 2004 generation of heavy diesels.

The paper is organized as follows: the background related to the formation of sulfur oxides and the sulfuric acid is presented first. The description of the experimental setup, including the condensate collection apparatus, is given next. This is followed by the condensate analysis technique for determining the concentration of sulfuric acid and indirect detection of SO₂, and the discussion of results. The paper ends with conclusions and recommendations for a possible extension of the study.

BACKGROUND

THE FORMATION OF SULFUR OXIDES AND SULFURIC ACID

During combustion of fossil fuels, fuel-bound sulfur is converted into sulfur oxides, predominantly into sulfur dioxide (SO₂). A small percentage is further oxidized to form sulfur trioxide (SO₃) [4]. The chemical equilibrium is highly dependent on temperature. The reaction from SO₂ to SO₃ is exothermic and equilibrium favors the formation of SO₃ as the temperature of the exhaust gas decreases. Equilibrium calculations are performed using the following reactions:



SO₃ is corrosive to the materials in the cylinder and downstream in the exhaust manifold. Furthermore it can react with water vapor present in the exhaust stream and form sulfuric acid (H₂SO₄).



If the exhaust gas is cooled below the dew point of water, remaining SO₂ can react with liquid water droplets to form sulfurous acid (H₂SO₃).



H₂SO₃ reacts with oxygen in the exhaust gas to form sulfuric acid.

Both sulfuric acid and sulfurous acid are highly corrosive, which leads to the possibility of reduced component life of the EGR system and intake systems.

Table 1 shows a brief overview of the sulfur oxidation reactions that occur in a combustion engine at different temperatures.

Table 1: Sulfur oxidation steps related to temperature

Temperature	Reaction	Location
2000°C	Mostly SO ₂ , traces of SO ₃	Combustion chamber
<730°C	Equilibrium starts to favor SO ₃ which reacts with water to form H ₂ SO ₄	Exhaust manifold
<165°C	Condensation and deposition of H ₂ SO ₄ starts	Exhaust manifold, EGR cooler, and Intake manifold
<70°C	Water vapor condenses and reacts with SO ₂ to form H ₂ SO ₃	EGR cooler and Intake manifold

Based on the chart, maintaining a higher exhaust gas temperature would:

- Avoid the formation of H₂SO₃ / H₂SO₄ from the reaction of SO₂ with liquid water
- Slow down the oxidation of SO₂ to SO₃ and its subsequent reaction with water vapor
- Avoid the condensation of any H₂SO₄ present in the EGR gas stream

However, this stands in direct contrast to the need to reduce NO_x formation by lowering the combustion temperature, hence the use of cooled EGR and an accompanying increased risk of corrosion. The purpose of our study is to establish methods for measuring sulfur oxides in the exhaust stream, assess the possibility of forming sulfuric acid in the gas stream, and help understand the risk and mechanisms of corrosion in the diesel engine with cooled EGR.

THE IMPACT OF SULFUR OXIDES ON EGR COOLER CONDENSATE

Sulfuric acid is particularly corrosive when it is present in a liquid form and can be deposited on the walls. Thus, the relationship between the heat exchanger temperature and the dew point of H₂SO₄ is very important. However, the dew point of sulfuric acid is difficult to determine since it is strongly correlated to the partial pressure of SO₃. Muller [5] has calculated the H₂SO₄ dew point as a function of SO₃ partial pressure with 10% water content by volume in Figure 1.

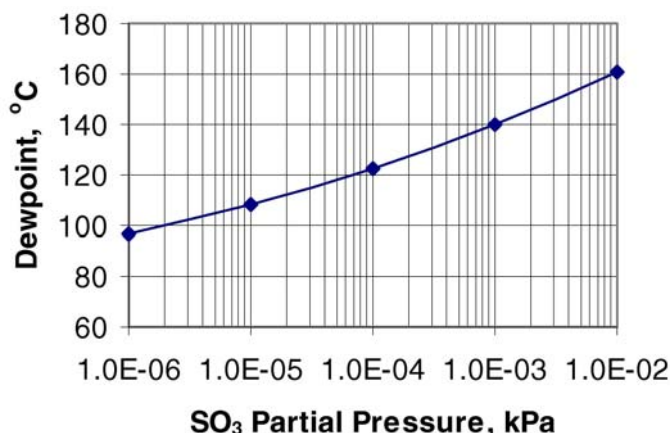


Figure 1: H₂SO₄ dew point vs. SO₃ partial pressure [4]

To demonstrate the impact of SO₃ partial pressure on the sulfuric acid dew point using Muller's [5] calculations, Girard et al. [4] determined temperature values of approximately 122°C for 1 ppm of SO₃ in the exhaust stream, and around 109°C for 0.1 ppm. The SO₃ partial pressure depends on factors such as temperature, sulfur content in fuel, availability of oxygen, and residence time in the exhaust manifold, which is not easy to calculate. Thus, the effect of EGR temperature and other factors on the sulfuric acid concentration and cooler fouling has to be investigated under realistic conditions in a multi-cylinder diesel engine, and that provides the motivation for our study.

SOOT FORMATION AND THE IMPACT OF FUEL SULFUR LEVEL ON PARTICULATE EMISSIONS

Soot particles from diesel exhaust mainly consist of unburned carbon and partially oxidized polycyclic aromatic hydrocarbons (PAH). These particles undergo a simultaneous formation and an oxidation process during the combustion. Obviously, their net release is the difference between formation and destruction. The formation process usually begins with the pyrolysis (high temperature fragmentation without sufficient oxygen) of PAH. They develop from very small precursors of particles to bigger ones through agglomeration with other particles. Ahmad et al. [6] proposed an equation that outlines the different parameters of soot formation:

$$\left[\frac{dm_c}{dt}\right]_{form} = A \cdot T \cdot (HC)^b \cdot (O_2)^{-c} \cdot e^{\frac{-E_{form}}{R \cdot T}} \quad (5)$$

where: A, b, c, and E_{form} are determined experimentally.

This equation shows that soot formation depends directly on fuel, inversely on oxygen, and exponentially on temperature. Thus, the higher the temperature the more soot will be formed. Ahmad et al. [6] however also proposed a correlation for the oxidation of soot:

$$\left[\frac{dm_c}{dt}\right]_{ox} = B \cdot (O_2)^d \cdot e^{\frac{-E_{ox}}{R \cdot T}} \quad (6)$$

where: B, d, and E_{ox} again are determined experimentally.

This equation demonstrates that the oxidation of soot also strongly depends on temperature. The higher the temperature, the more soot can be oxidized. The net soot release is finally described by the difference of soot formation and oxidation:

$$\left[\frac{dm_c}{dt}\right]_{net} = \left[\frac{dm_c}{dt}\right]_{form} - \left[\frac{dm_c}{dt}\right]_{ox} \quad (7)$$

It was found experimentally that soot formation starts at local combustion temperatures between 1500 to 1600 K. If the temperature exceeds around 1900 K, soot oxidation starts to occur rapidly, and for even higher temperatures the net soot release will decrease. Thus, either very low (<< 1500 K) or very high (>> 1900 K) combustion temperatures have to be achieved to lower net soot release from the engine.

Exhausted particles from a diesel engine not only contain organic compounds like PAH, but they might contain traces of metals and sulfates (SO₄⁻²) formed from the sulfur in fuel. Yost et al. [3] investigated the influence of sulfur level in JP-8 fuel on particulate matter and sulfate emissions. JP-8 fuel had been doped with di-tert-butyl-disulfide (DTBDS), to obtain sulfur concentration of 600, 1100, and 2600 ppm. Their experiments were performed on two different engines. In both cases, sulfur concentration in fuel had a strong influence on the emissions of particulate matter. The amount of sulfates trapped in the particles increased with the fuel sulfur concentration. Similar results were found by Hori and Narusawa [7]. Sulfate-containing soot particles can be deposited in the EGR cooler. Contact between the deposits/sulfates in the cooler and condensed water can also produce sulfuric acid in addition to its direct forming from reaction of sulfur oxides with water vapor. It is important to analyze the gas phase and complement that with measurements of the overall level of PM in order to gain insight into the relative importance of either process.

EXPERIMENTAL SETUP

ENGINE

The engine used in this study is a Detroit Diesel Corporation (DDC) Series 60 heavy-duty diesel engine. It is equipped with electronically controlled unit injectors, variable geometry turbocharger (VGT), charge air intercooler, and exhaust gas recirculation (EGR) with EGR cooler. The engine is fully instrumented for measuring pressures, temperatures and flows. Table gives an overview of the engine specifications.