

Hydrocarbons and Particulate Matter in EGR Cooler Deposits: Effects of Gas Flow Rate, Coolant Temperature, and Oxidation Catalyst

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ABSTRACT

Compact heat exchangers are commonly used in diesel engines to reduce the temperature of recirculated exhaust gases, resulting in decreased NO_x emissions. These exhaust gas recirculation (EGR) coolers experience fouling through deposition of particulate matter (PM) and hydrocarbons (HCs) that reduces the effectiveness of the cooler. Surrogate tubes have been used to investigate the impacts of gas flow rate and coolant temperature on the deposition of PM and HCs. The results indicate that mass deposition is lowest at high flow rates and high coolant temperatures. An oxidation catalyst was investigated and proved to effectively reduce deposition of HCs, but did not reduce overall mass deposition to near-zero levels. Speciation of the deposit HCs showed that a range of HCs from C₁₅ – C₂₅ were deposited and retained in the surrogate tubes. Analysis of the deposit mass of eicosane (C₂₀) showed that the deposition of HCs is very sensitive to the coolant temperature in the range investigated. The results suggest that use of an oxidation catalyst and/or reduction of the amount of high-boiling point HC species in the fuel may be pathways toward reduced EGR cooler fouling.

INTRODUCTION

Exhaust gas recirculation (EGR) has proven to be a useful means of reducing NO_x formation during the combustion process in compression-ignition engines for both conventional and low-temperature combustion modes. [1-5] Compact heat exchangers are now commonly installed to cool the EGR gases prior to mixing with the fresh air charge, further reducing NO_x formation. EGR coolers experience degradation of performance as a result of the buildup of PM and HCs in the gas-side flow paths of the cooler. These form a deposit layer that is less thermally conductive than the stainless steel of the tube enclosing the gas, resulting in

lower heat exchanger effectiveness. [6-7] Low-pressure loop EGR systems are not as sensitive to fouling because they recirculate exhaust from downstream of a diesel particulate filter and are exposed to less PM. In the past, EGR coolers were sufficiently large and the NO_x targets sufficiently high that the cooler fouling process was of less importance. Smaller, more efficient coolers are beneficial from both a cost and packaging standpoint. However, as evidenced by the number of ongoing studies, maintaining the EGR cooler at a high level of performance has become a significant issue in terms of achieving compliance with increasingly stringent NO_x regulations. [8-15]

The EGR cooler fouling process is a complex interaction involving turbulent mixing, thermophoresis, Brownian motion, and condensation. At least five characteristics significantly influence EGR cooler fouling processes. These are the gas temperature at the cooler inlet, the coolant temperature, the gas flow rate, the PM concentration, and the HC concentration. The temperature gradient imposed by the difference in the gas temperature and the coolant temperature produces a thermophoretic driving force that influences the deposition of PM on the cooler walls. The coolant temperature also influences condensation of gas-phase HCs on the relatively cold walls of the cooler. PM and HC concentrations are important because they describe the amount of material available for deposit formation. Lastly, the EGR flow rate is important because it influences the time available in the cooler for migration of material to the tube surface. High gas flow velocities are also suspected to provide a "removal mechanism" to further reduce deposit formation.

Parametric study of these variables is needed to fully understand the relationships among the variables as they relate to the fouling process. Unfortunately, it is not usually possible to independently vary all five of these variables in an engine. Low combustion temperatures,

for example, may reduce PM, but almost always cause changes in the HC concentration and/or speciation as well as differences in exhaust gas temperature. Changing the EGR flow rate typically cause changes to the PM level and often the exhaust gas temperature. Changes in coolant temperature also create similar confounding effects to other key variables. Adding to this complexity, EGR coolers are often inconvenient in terms of deposit analysis because of their size and shape. (Assessing the deposits usually requires destructive tear-down of the cooler.) Use of a surrogate cooler that can enable independent variation of the key variables and provide cost-effective, convenient access for studying the deposits is an attractive alternative. This study reports the use of such an approach to investigate the effects that EGR flow rate and coolant temperature have upon the deposition of PM and HC species in individualized surrogate cooler tubes.

APPROACH

ENGINE AND ENGINE OPERATING CONDITIONS – A model year 1999 Mercedes 1.7-liter common-rail diesel engine was used as an exhaust gas generator for this study. Table 1 shows the relevant engine characteristics and operating conditions for this study. Standard instrumentation was used for measurement of exhaust constituents, including heated HC and NO_x instruments, non-dispersive infrared instruments for carbon monoxide and carbon dioxide, and paramagnetic instruments for oxygen.

Table 1. Engine specifications and operating conditions.

Engine	Mercedes 1.7L turbo diesel (OM668, MY 1999)
Fuel System	Bosch Common Rail 6 holes 0.169 mm diameter per injector
Bore x Stroke, mm	80 x 84
Compression Ratio	19.5
RPM	2000
Load	16 ft-lb
Boost pressure	0.2 psig
EGR rate	30%
Fuel Injection Settings	2 injections, pilot + main Pilot Injection 261 μs duration @ 26.6 CAD BTDC Main Injection 504 μs duration @ 5.0 CAD BTDC Fuel Rail Pressure 338 Bar
Exhaust Temperature (at sample location)	250°C
Exhaust Pressure (at sample location)	7 PSIG
Filter Smoke Number	0.83 – 1.47 FSN
Engine out THC	416-648 ppmC ₁

PM was measured using an AVL model 415S smoke meter. The smoke meter does not provide a true gravimetric measurement of PM mass, but is a convenient and broadly accepted measurement.

A certification diesel fuel containing 300 parts-per-million by weight (PPMw) sulfur was used for this study. This fuel was selected because a sizeable number of diesel vehicles in the North American marketplace may still be used in off-highway applications and thus may be exposed to fuel with sulfur levels higher than 15 PPMw. The fuel was sourced from Chevron-Phillips Specialty Chemical Company. The engine operating parameters were selected to produce a fairly low-temperature condition with a significant amount of PM and HC in the feedgas to the surrogate tubes.

SURROGATE EGR COOLER TUBES – This study focused on use of individualized shell-and-tube heat exchangers to allow study of the fouling process. These heat exchangers used a single 6.35-mm diameter 316-stainless steel tube 305-mm in length as a surrogate EGR cooler tube. The tube wall thickness was 0.71-mm. The surrogate tubes were individually surrounded by simple shell-type cooling jackets fabricated using Swagelok™ fittings and removable ferrules. Six surrogate tubes were used for each experiment. Two of the tubes were heated to 190°C to serve as “non-fouling” reference tubes and are referred to as heated tubes. 190°C is a common setpoint for heated gas sampling lines to avoid condensation of hydrocarbons during diesel exhaust sampling. This temperature was utilized in this study for the same reason. Two tubes were exposed to the untreated exhaust flow and are referred to as cooled tubes. A small oxidation catalyst core was placed in front of each of two of the tubes to examine the potential benefit of using an EGR catalyst. These tubes are referred to as catalyzed tubes. The catalyst cores were sized so that the maximum catalyst space velocity for this study was 250,000 hr⁻¹ at the maximum flow rate. The fixed catalyst volume meant that the lower flow rate conditions had equivalently lower catalyst space velocities. With the exception of the heated reference tubes, all tubes were cooled using the same coolant temperature for each experiment. Three different coolant temperatures were studied: 85°C, 70°C, and 40°C. These setpoint were selected to approximate the range of temperatures that might be experienced in a current or near-term EGR cooler application. The surrogate tube gas flow rates investigated were nominally 30 standard liters per minute (SLPM), 15-SLPM, and 5-SLPM per tube. All permutations of coolant temperature and gas flow rate were tested. A manifold was fabricated to connect the inlets for all six tubes. The sampling apparatus was connected to the engine exhaust manifold upstream of the turbocharger inlet. The tubes were exposed to engine exhaust for 2 hours during each experiment. Previous experiments had shown that 2 hour exposures were sufficient to produce quantifiable deposits for analyses, but were short enough to permit large numbers of experiments to be completed in a reasonable amount of time.

SURROGATE TUBE ANALYSES – This study focused on characterizing the PM and hydrocarbon species retained in the surrogate tubes. The total deposit mass gained by each tube was characterized by weighing each tube before and after exposure to engine exhaust. A balance with a least count of 0.1-mg was utilized. The tubes were equilibrated prior to weighing by placing them in a constant temperature and humidity environment overnight. This procedure was necessary to reduce errors associated with retention of small amounts of water by the tubes.

After the deposit mass was measured, the tubes were put through a solvent extraction process to remove the HCs for analysis. A base-neutral-acid extraction process was used to force all of the species in the deposit into a solvent-phase (methylene chloride). First several milliliters of a base (1 normal sodium hydroxide) was placed into each tube with an equal portion of methylene chloride and sonicated briefly. The resulting deposit slurry was poured from each tube into a separate vial. Next several milliliters of an acid (1 normal sulfuric acid) and an equal portion of methylene chloride were added to each tube and sonicated. This was then poured into the same vials as the previous slurry. Finally, a rinse of several milliliters of methylene chloride was placed in each tube and sonicated briefly, and this final rinse again added to the vials. Each vial (corresponding to an individual tube) was then allowed to settle to allow the aqueous and solvent phases to separate. After separation the solvent phase was removed using a disposable pipette and placed in a separate vial for analysis by gas chromatography / mass spectroscopy (GC/MS). These samples often required subsequent dilution with solvent to maintain the analytes within the dynamic range of the GC/MS. Unfortunately, a consequence of the focus on solvent extraction followed by GC/MS analysis meant that no direct mass measurement of the solvent-extracted PM was possible.

RESULTS

DEPOSIT MASS GAIN - Figures 1-3 show the deposit mass gains for the 5-, 15-, and 30-SLPM flow rates, respectively. Data are shown individually for all 6 tubes (A-F), with the coolant temperature increasing to the right in each group of bars. The duplicate tubes for each condition show good agreement for each set of experiments. There were, in all cases, near-zero mass gains in the heated tubes. This fact verifies that the observed mass gains in the cooled and catalyzed tubes are the result of variations in the gas flow rate and coolant temperature.

There are interesting observations to be made regarding the interactions between the test factors. Referring to Figure 4, clearly the most significant observation is that the mass gain is greatest at the 40°C coolant temperature except at the low flow case (5-SLPM)

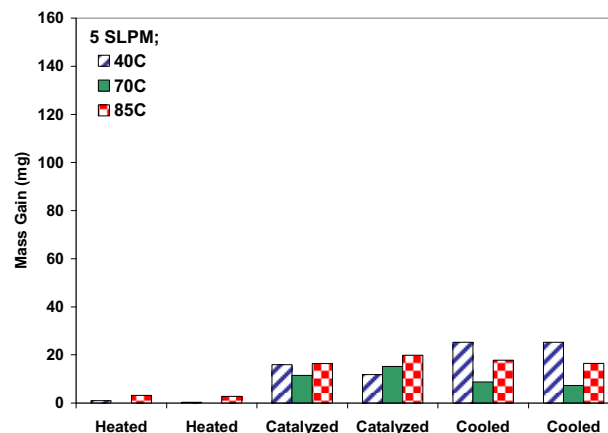


Figure 1. Deposit mass gains for the 5-SLPM flow rate.

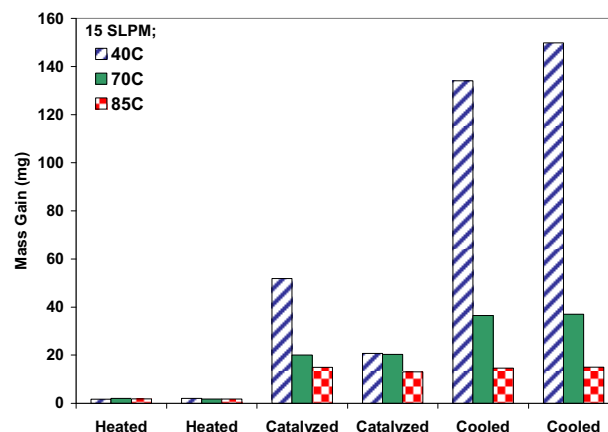


Figure 2. Deposit mass gains for the 15-SLPM flow rate.

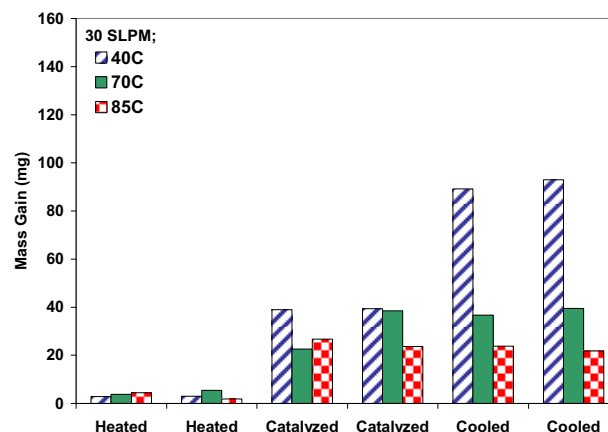


Figure 3. Deposit mass gains for the 30-SLPM flow rate.