

Combination of Pre-EGR Cooler Oxidation Catalyst and Water Vapor Condensation to Mitigate Fouling

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ABSTRACT

Cooled exhaust gas recirculation (EGR) is widely used in diesel engines to control engine out NO_x (oxides of nitrogen) emissions. A portion of the exhaust gases is re-circulated into the intake manifold of the engine after cooling it through a heat exchanger known as an EGR cooler. EGR cooler heat exchangers, however, tend to lose efficiency and have increased pressure drop as deposit forms on the heat exchanger surface due to transport of soot particles and condensing species to the cooler walls. In our previous work surface condensation of water vapor was shown to be successful in removing a significant portion of the accumulated deposit mass from various types of deposit layers typically encountered in EGR coolers. Significant removal of accumulated deposit mass was observed for "dry" soot only deposit layers, while little to no removal was observed for the deposit layers created at low coolant temperatures that consisted of both soot and condensed hydrocarbons (HC). The focus of this study was to explore the potential benefits of combining a pre-EGR cooler oxidation catalyst (OC) in the high pressure EGR loop with exposure to water vapor condensation. The catalyst oxidized close to 90% of inlet hydrocarbons at the conditions used in this study, thereby, preventing condensation in the EGR cooler downstream. Subsequent exposure to surface condensation of water vapor resulted in significant removal of deposit mass from these 'dry' soot only deposit layers. Addition of the oxidation catalyst in the high pressure EGR loop resulted in minimal additional pressure drop (< 2kPa) over the range of conditions tested in this study. Based on the findings in this study addition of a pre-EGR cooler oxidation catalyst to the high pressure EGR loop can offer several advantages such as mitigation of cooler fouling, expanded cooler operating range at the high hydrocarbon concentration points in the engine map and reduction in calibration complexity.

CITATION: Warey, A., Bika, A., Vassallo, A., Balestrino, S. et al., "Combination of Pre-EGR Cooler Oxidation Catalyst and Water Vapor Condensation to Mitigate Fouling," *SAE Int. J. Engines* 7(1):2014, doi:10.4271/2014-01-0636.

INTRODUCTION

Strict emissions regulations have been implemented worldwide to limit the pollutant emissions from diesel engines. Particulate matter (PM) in diesel exhaust consists of a solid fraction commonly referred to as soot, a soluble organic fraction (SOF) and sulfates. The solid fraction is mostly carbon, which consists of molecules with C/H ratios ranging from 4 to 11. The solid fraction is commonly referred to as soot and it makes up the core of the particulate. Morphologically, it consists of nearly spherical primary particles that cluster to form chain like aggregates. The SOF consists of organic compounds with C/H ratios of 0.5-1.0. This includes the polycyclic aromatic hydrocarbons (PAH) and partially oxidized products such as aldehydes and alcohols. The sulfate content of PM is derived from sulfur in the fuel and lubricating oil [1], [2].

The widely used methodology for reducing NO_x emissions from diesel engines is to re-circulate a portion of the exhaust gases into the combustion chamber after cooling them in a heat exchanger known as an EGR cooler. Deposition of particulate matter on the walls of the EGR cooler leads to formation of a fouling layer [2]. The fouling of EGR coolers results in significant deterioration of the cooler effectiveness and increased pressure drop across the cooler. This adversely affects the combustion process, engine durability and emissions. Since the pressure differential between the exhaust and intake manifolds is the driving mechanism for EGR flow, an increase in pressure drop across the EGR cooler also affects control of the desired EGR rate and results in decreased fuel efficiency due to increased pumping work [2].

There have been many recent investigations related to EGR cooler fouling [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. It has been extensively reported from these studies

that thermophoresis is the dominant mechanism for deposition of submicron particles in EGR coolers. Thermophoresis is particle motion in the presence of a temperature gradient. Collisions with more energetic gas molecules on the hot gas side versus the cold gas molecules near the channel wall leads to net motion of particles towards the wall [9]. Lance et al. [16], [17] directly measured the thermal properties of EGR cooler deposits and found that the soot cake formed on cooler walls is approximately 98% porous. They determined that the porosity of the deposit has a strong influence on the low thermal conductivity (~ 0.041 W/m-K) of the deposit layer.

Condensation of hydrocarbons (HC) in diesel exhaust occurs in the EGR cooler as well under certain boundary conditions and is a function of the vapor pressure and concentration of the HC species. Sluder et al. [3] investigated the role of hydrocarbons in EGR cooler deposit formation and found that deposition of hydrocarbons on the cooler walls is very sensitive to the coolant temperatures used in EGR coolers. They found that the gas chromatograph/mass spectrometer (GC/MS) chromatograms for deposits in surrogate tubes fouled by exhaust from a diesel engine had a peak approximately around C_{19} - C_{20} , both of which are present in diesel fuel in significant quantities. They also found that the tube cooled by coolant at 40 °C temperature retained hydrocarbons as light as C_{15} . Lance et al. [17] from their optical microscopy measurements on deposits from field fouled EGR coolers found that the cold cooler walls inhibit the evaporation of the condensed species.

Abarham et al. [18] used a test stand to visualize condensation of water vapor on the walls of a surrogate rectangular channel cooler exposed to diesel exhaust flow. They observed formation of water droplets on the cooler wall as the coolant temperature was lowered to 20 °C. Cracks developed in the deposit layer and significant fragments of the layer flaked off when the surface temperature was low enough to cause water condensation.

Based on a surface condensation model that we developed and published previously [16], [12], [16], [14], condensation of water vapor in the exhaust to the cooler walls is expected below 50 °C coolant temperature as shown in Figure 1.

An extensive experimental study was conducted to investigate whether this surface condensation of water vapor could be used to remove the accumulated deposit mass from various types of deposit layers typically encountered in EGR coolers [19]. Effect of water vapor condensation on three different deposit layers systematically created to represent deposits typically found in EGR coolers was investigated. The first two deposit layers were "dry" soot only layers, while the final deposit layer consisted of soot as well as condensed hydrocarbons. Significant removal of accumulated deposit mass was observed for the "dry" soot only deposit layers created at 50 and 100 °C coolant temperatures, while little to no removal was observed for the deposit layer created at 25 °C

coolant temperature and high exhaust HC concentration that consisted of both soot and condensed HC's. Even 5 minutes of exposure to water vapor condensation was sufficient to cause significant deposit removal. No evidence of condensation or removal was observed above 40 °C coolant temperature. In addition, it was observed that the soot only layers were hydrophobic, while the deposit layer that contained condensed HC's was hydrophilic. Based on the findings in the study it was hypothesized that the disruption of the hydrophobic porous soot layer due to formation of condensed water droplets underneath was responsible for the removal of deposit mass with gas flow. For the deposit layer created at 25 °C coolant temperature and high exhaust HC concentration a reduction in porosity and increase in thermal conductivity due to condensed hydrocarbons inhibited diffusion of water vapor through the deposit layer resulting in condensation of water vapor on the surface of the deposit layer rather than underneath. The condensed water droplets rolled off the surface due to gas flow and water/hydrocarbon immiscibility leading to very little removal of the deposit mass.

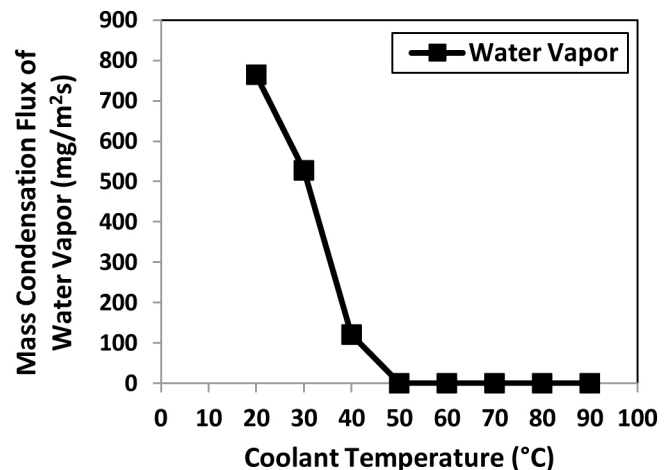


Figure 1. Mass condensation flux of water vapor to the surface as a function of coolant temperature [14]

Several researchers have investigated the use of a pre-EGR cooler oxidation catalyst in the high pressure EGR loop to mitigate fouling [16], [20], [16], [21], [16], [22]. The oxidation catalyst can mitigate fouling by oxidizing the hydrocarbons present in the exhaust stream thereby preventing condensation of HC's in the EGR cooler. The total HC conversion efficiency of the catalyst depends on the space velocity and its light-off temperature. In the high pressure EGR loop, the space velocities through the catalyst can be relatively high due to packaging constraints. On the other hand the high HC concentration points in the engine map typically occur at light loads, where the exhaust gas temperature might be below the catalyst light-off temperature resulting in poor HC conversion efficiencies. Hence, it is essential to design the catalyst to maximize the HC conversion efficiency at exhaust conditions typically encountered in the high pressure EGR loop.

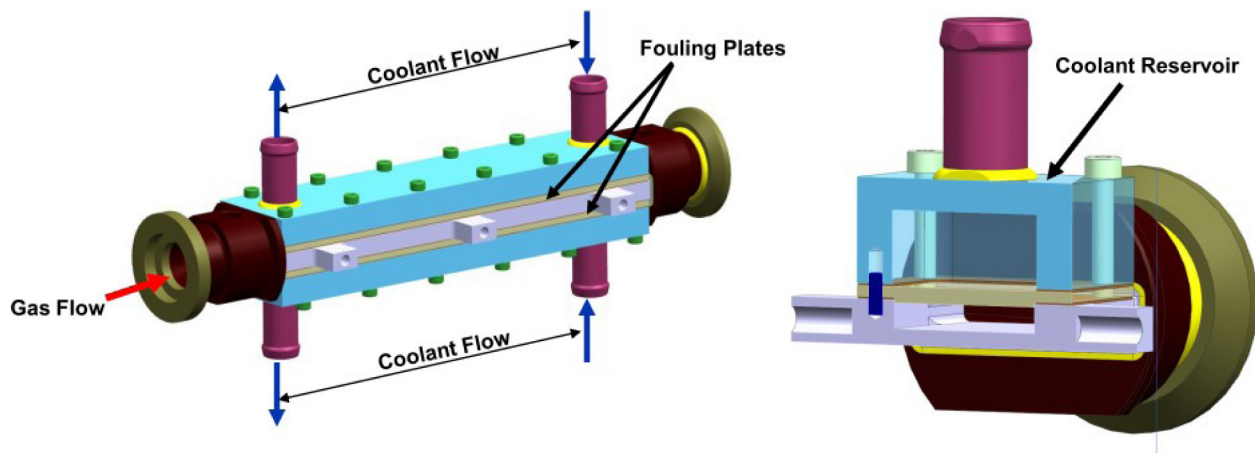


Figure 2. Single rectangular channel take-apart EGR cooler used in the study

The focus of this study was to investigate whether the benefits of a pre-EGR cooler oxidation catalyst and surface condensation of water vapor could be combined to mitigate fouling. It was experimentally shown in a prior study that surface condensation of water vapor could be used to remove “dry” soot only deposit layers in the EGR cooler [19]. In this work an experimental study was conducted to investigate if a pre-EGR cooler catalyst could be used to oxidize the HC’s present in the exhaust stream thereby preventing condensation of HC’s in the EGR cooler and keep the deposit layer “dry”. This “dry” deposit layer could then be removed by short exposure to water vapor condensation by adjusting the engine operating conditions. By preventing the condensation of HC’s the pre-EGR cooler oxidation catalyst could broaden the operating regime of the EGR cooler where the deposit layer remained “dry” allowing for removal by exposure to surface water vapor condensation, where previously removal was unlikely. Use of a pre-EGR cooler catalyst would result in a passive addition to the high pressure EGR loop with no regeneration required unlike a particulate filter.

EXPERIMENTAL SETUP

EGR Cooler

A custom built single rectangular channel take-apart EGR cooler was used in this study as shown in Figure 2. The cooler consisted of two parallel rectangular stainless steel plates, 2.5 mm thick and 200 mm length, that made up the gas flow channel. The outer surface of each plate was connected to an individual coolant reservoir that was used to maintain the plates at a relatively fixed surface temperature. A mixture of ethylene glycol and water was used as the cooling fluid. The coolant temperature and flow to the EGR cooler were independently controlled, using a circuit that was separate from the engine. The coolant was circulated through both reservoirs in a counter-flow configuration with respect to the exhaust gas flow and its flow rate was measured with a turbine flow meter.

The coolant flow was maintained at a rate high enough (roughly 5 GPM) to ensure there was no discernable temperature difference between the inlet and outlet coolant temperatures. Temperature measurements were also made at the gas inlet and outlet of the EGR cooler. After exposure to fouling conditions the cooler was disassembled and both the top and bottom plates were weighed using a Sartorius M-Power model # AZ214 scale to determine accumulated deposit mass. For some experiments the plates were aged in Forma Scientific 6512 vacuum oven at 250 °C and 7 in-Hg vacuum for two hours prior to weighing. At the end of a day’s testing both plates were thoroughly cleaned and the clean weights were recorded. Clean weights for both plates were within 0.01% on different days of testing.

Engine Test Stand

Experimental testing was conducted on a 1.9 L multi-cylinder common-rail diesel engine. Engine parameters such as fuel injection timing, duration, rail pressure, swirl ratio, and intake manifold boost pressure, were controlled using an aftermarket electronic control unit manufactured by Driven Inc. The engine was coupled to an alternating current dynamometer for load and speed control. The engine specifications are given in Table 1.

Table 1. Engine Specifications

# of Cylinders	4
Displacement (L)	1.9
Bore (mm)	82
Stroke (mm)	90.4
Compression ratio	17.5:1
Fuel Injection System	Common Rail
Turbocharger	Variable Geometry Turbine
# of Cylinders	4
Displacement (L)	1.9



Documents

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A prototype EGR system was configured to isolate the EGR cooler from the engine and maintain constant inlet boundary conditions at the cooler inlet. This was accomplished by re-routing the EGR cooler outlet into the tailpipe downstream of the turbocharger, instead of the original routing configuration into the intake manifold. The EGR system modification was made after difficulty was encountered in maintaining a stable operating condition as the EGR cooler began fouling. Flow through the modified EGR circuit was regulated using an electrically controlled valve (EGR Bypass valve) downstream of the cooler. The stock EGR valve on the engine was kept fully closed during all the tests in the study so that there was no EGR flow into the intake manifold. This bypass system allowed the EGR circuit to operate through a range of flows that would typically be encountered on a production engine application. The flow rate through the EGR cooler (M_{EGR}) was determined by introducing a known flow of CO₂ free clean air ($M_{cleanair}$) into the tailpipe downstream of the EGR cooler and measuring the engine out CO₂ concentration ($CO_{2,in}$) with an exhaust gas analyzer upstream of the EGR cooler and the CO₂ concentration downstream of the EGR cooler ($CO_{2,out}$) with a CO₂ analyzer after mixing with the clean air. The approach was analogous to conventional EGR flow rate measurements made by using engine-out and intake manifold CO₂ concentrations. The flow rate through the EGR cooler (M_{EGR}) was calculated as:

$$M_{EGR} = M_{clean\ air} \frac{CO_{2,out}}{CO_{2,in} - CO_{2,out}}$$

(1)

A schematic of the engine test stand is shown in Figure 3. An AVL 415S smoke meter was used to measure the filter smoke number (FSN) downstream of the turbocharger. Ultra low sulfur diesel fuel (ULSD) was used for the study.

Oxidation Catalyst

A metallic longitudinal structure (LS) foil oxidation catalyst manufactured by Emitec, Inc. was used in the study. Specifications of the catalyst are given in Table 2.

Table 2. Oxidation Catalyst Specifications

Diameter	mm	45
Length	mm	120
Cell Density	cpsi	200 LS
Volume	L	0.19
Washcoat	g/ft ³	67.5 g/ft ³ Pt / 22.5 g/ft ³ Pd

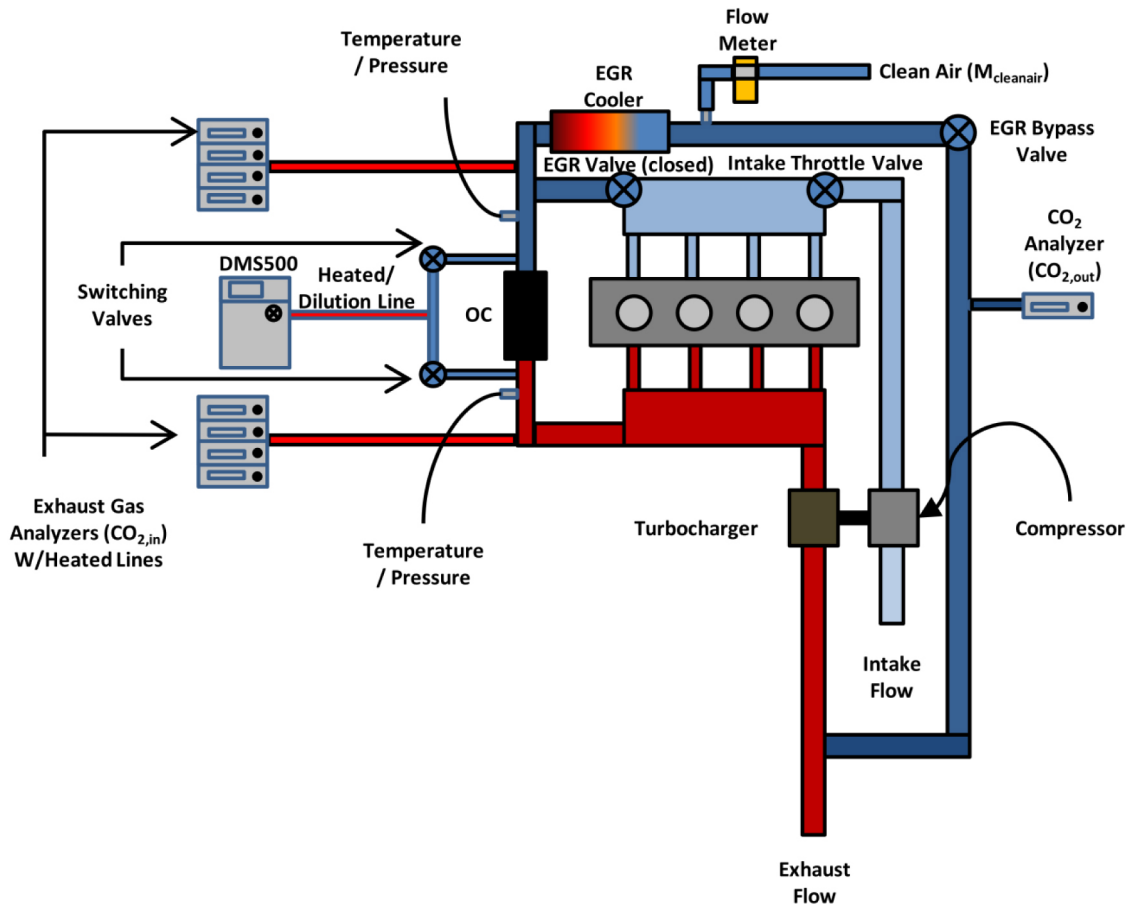


Figure 3. Schematic of the engine test stand