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Influence of water vapor condensation on exhaust gas recirculation cooler 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. The focus of this study was to investigate whether 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. Both visual and quantitative evidence of water vapor condensation and deposit removal were collected. A multi-cylinder diesel engine was used to produce three different deposit layers in a custom built single rectangular channel EGR cooler. The deposit layers were then exposed to water vapor condensation over a range of coolant temperatures, flow rates and exposure times by adjusting the engine operating conditions. Significant flaking and removal of deposit layers made up of mostly soot particles was observed when exposed to condensation of water vapor even with an exposure duration as low as 5 min. However, very little removal of deposit mass with exposure to water vapor condensation was observed when the deposit layer consisted of condensed exhaust hydrocarbon species in addition to soot. In addition to engine experiments a visualization test rig was setup to visualize condensation of water vapor from clean humid air and its effect on different deposit layers. Surface condensation of water vapor can lead to significant removal of certain deposit layers from the cooler walls and, thus, mitigate fouling of the EGR cooler. It could potentially be used as regeneration strategy for periodic on-board regeneration of fouled EGR coolers.

1. 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 [3–15]. It has been extensively reported from these studies that thermophoresis is the dominant mechanism for deposition of submicron particles under non-isothermal conditions.

Abbreviations: ATDC, after top dead center; CAD, crank angle degree; EGR, exhaust gas recirculation; HC, hydrocarbons; NO_x, oxides of nitrogen; PM, particulate matter; SOF, soluble organic fraction; ULSD, ultra low sulfur diesel fuel.

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Thermophoresis is particle motion in the presence of a temperature gradient. Collisions with more energetic gas molecules on the hot gas side vs. the cold gas molecules near the channel wall leads to net motion of particles towards the wall [8]. 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.

Kern and Seaton [18] were the first to offer a formulation of the removal term for heat exchanger deposits. They defined an average removal rate, which is assumed to be caused by shearing action of the stream at the surface. Rather than being removed particle by particle, deposit is considered to be sheared off in fragments [19]. They postulated that the average removal rate over the whole tube would be roughly proportional to the shear stress and thickness of the deposit. Yung et al. [20] did visualization experiments and concluded that fluid drag force was the dominant re-entrainment force. They showed that if the drag force is larger than the adhesion force for small particles, removal occurs. Müller-Steinhagen et al. [21] and Grillot and Icart [22] have shown that when the gas velocity is increased particulate fouling is generally reduced. It was found that particulate fouling can be avoided if the gas velocity is above a critical flow velocity [9]. The critical flow velocity is defined as the bulk velocity above which rolling of the deposited particles occurs.

Abarham et al. [23] 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 [24].

Based on a surface condensation model that we developed and published previously [11,14], condensation of water vapor in the exhaust to the cooler walls is expected below 50 °C coolant temperature as shown in Fig. 1. The focus of this study was 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. There are several differences between the present work compared to the investigation of Abarham et al. [23,24]. In the present study both visual and quantitative evidence of water vapor condensation and deposit removal were collected. Effect of water vapor condensation on three different deposit layers systematically created to represent deposits typically found in EGR coolers was investigated. After creation of the deposit layer on the engine, it was exposed to clean humid air flow on the visualization test rig to isolate the effect of water vapor condensation from other condensing exhaust species such as sulfuric and nitric acid. The deposit layers were also exposed to water vapor condensation directly on the engine by adjusting the operating conditions. The deposit layers were exposed to relatively clean engine exhaust over a range of EGR coolant temperatures, flow rates and exposure times.

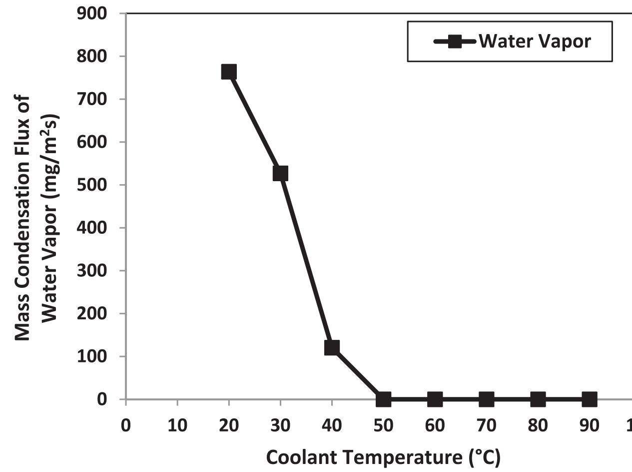

Fig. 1. Mass condensation flux of water vapor to the surface as a function of coolant temperature [14].

2. Experimental setup

2.1. EGR cooler

A custom built single rectangular channel take apart EGR cooler was used in this study as shown in Fig. 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. After exposure to water vapor condensation, the plates were dried in Forma Scientific 6512 vacuum oven at 200 °C and 7 in-Hg vacuum for 2 h. Both plates were then weighed again to determine the amount of deposit mass removed due to water vapor condensation. 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.

2.2. 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 Drivven Inc. The engine was coupled