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The effect of engine operating conditions on exhaust gas recirculation cooler fouling ☆

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ABSTRACT

Exhaust gas recirculation (EGR) cooler fouling occurs when particulate matter (PM) and hydrocarbons (HC) in diesel exhaust form a deposit on the walls of the EGR cooler through thermophoresis and condensation. To better understand the mechanisms controlling deposit formation and removal and how operating conditions can affect cooler performance, 20 identical tube-in-shell EGR coolers with sinusoidal fins were fouled using a 5-factor, 3-level experimental design. The deposit thickness was measured using two methods: (1) epoxy-mounting and polishing cooler cross-sections and comparing deposit thicknesses on the primary (outer tube) to the secondary (fins) heat transfer surfaces, and (2) milling tube sections such that the surface of a fin could be observed and measuring the deposit thickness across the fin using a 3D profilometer. Near the cooler inlet, high inlet gas temperatures reduced deposit thickness by promoting mud-cracking and spallation. Near the middle of the cooler, the flow rate had the largest impact on the deposit thickness through the effect on residence time of the PM. The HC concentration along with flow rate had the largest effects near the cooler outlet where the lower temperatures allows for more HC condensation. These insights into how engine operating conditions influence the development of fouling layers in EGR coolers learned through this study will aid in the development of more fouling resistant coolers in the future.

1. Introduction

Throughout the developed world strict regulations have been enacted to reduce the emission of harmful pollutants, such as nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM), produced by diesel engines. For NO_x emissions, the limits have decreased from 9.2 g/kW-hr in 2002 to just 0.40 g/kW-hr in 2014 for many classes of off-road compression-ignition engines in the United States [1]. This has placed increased importance on engine technologies for preventing NO_x formation as well as technologies for removing NO_x from exhaust gases. A commonly used method to control NO_x formation is exhaust gas recirculation (EGR) whereby a fraction of the engine exhaust is recirculated back to the combustion chambers. The introduction of inert exhaust gas, which is composed primarily of nitrogen, carbon dioxide and water vapor, increases the heat capacity of the cylinder contents. This increased specific heat acts to reduce combustion temperatures, thereby decreasing the formation of oxides of nitrogen [2]. Before being re-introduced into the cylinder, the exhaust gas is normally cooled in a heat exchanger, or cooler, which enhances the EGR effect.

Some particulate matter and hydrocarbon present in the exhaust gas will form a deposit inside the EGR cooler through thermophoresis and condensation [3]. Due to the high concentrations of PM and HC in the exhaust gas, these deposit layers can form rapidly. Furthermore, under most conditions, the deposits are excellent thermal insulators [4], negatively impacting the effectiveness of the EGR cooler. The reduced effectiveness of the cooler results in an increase in the temperatures of the exhaust gas re-introduced into the engine cylinders and, in turn, NOx pollutants generated during combustion. In addition, as the deposit thickens, it will impede the flow of exhaust gases through the cooler, causing an increase in the pressure drop across the cooler. This results in a loss in fuel efficiency as more energy must be expended to drive the exhaust gas through the cooler [3,5].

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Previous studies have focused on deposit formation and removal on flat tubes [6–13], but less work has been reported on substrates with turbulation structures that are typically used in production EGR coolers. Malayeri et al. examined the performance of a corrugated tube and found that the initial benefits resulting from the mixing enhancement induced by the corrugations is lost as deposits form in the grooves [14]. Their results showed that once fouled, the corrugated tube is outperformed by a simple plate-fin cooler. Kuan et al. developed a 1D EGR cooler fouling model, which included an empirical model for deposit removal, to examine various cooler geometries including those with sinusoidal fins [15]. Al-Janabi et al. used experiments to examine the effect of four different turbulation structure configurations heat transfer performance and fouling layer development [16]. They found that the orientation of the turbulation structures had a significant influence on heat transfer enhancement. Using experiments, Hooman et al. investigated the effects of blockage ratio, pore size and gas velocity on performance and fouling in metal foam EGR coolers [17]. Comparing the performance before and after fouling, they found that metal foams with 40 PPI (pores per inch) produced superior heat transfer performance compared to flat plate cooler designs.

Field-returned coolers have been observed to have microstructural features on the deposit surface that suggest that deposit removal is occurring on the upstream side of the fins during operation where shear stresses are high [18]. Previous attempts to image EGR deposits nondestructively using neutron tomography and thereby characterize how the turbulation structures impact deposition and removal were successful for high-HC plugging deposits but produced mixed results for low density deposit layers that are far more common in the field [19].

In this work, deposit formations in full production EGR coolers fouled under varied operating conditions were examined to understand how those conditions impact the fouling layer thickness. A five-factor, three-level design-of-experiments and statistical analysis method was used to determine how the EGR flow rate, EGR inlet gas temperature, coolant temperature, soot level and hydrocarbon concentration affected the thickness of the deposit near the inlet, middle and outlet of a production cooler with sinusoidal turbulation structures. Results from this analysis indicate that the thickness of the deposit decreases along the length of the channel even once the cooler appears to achieve steady-state with the effectiveness stabilized and further growth of the fouling layer halted. Furthermore, the dominant factors influencing the deposit thickness vary along the length of the cooler. These results provide valuable insights into the physical mechanisms driving the formation of fouling layers in production EGR coolers, which will aid in the development of more fouling resistant coolers.

2. Methodology

2.1. Experimental procedure

A 9-L heavy-duty (HD) engine running on ultra-low sulfur diesel (ULSD) fuel was used to foul 20 EGR tube-in-shell coolers by varying five factors: (A) EGR flow rate, (B) EGR inlet gas temperature, (C) coolant temperature, (D) smoke level (FSN), and (E) hydrocarbon (HC) concentration. Table 1 shows the target operating conditions with the corresponding standard deviations of the operating conditions achieved in experiments. With the exception of the low setpoint of the EGR inlet gas temperature and the low and middle setpoints of the smoke level, the average experimental values of the operating conditions differed by 5% or less from their target value. For the low setpoint of the EGR inlet gas temperature, the average experimental value differed by approximately 8% from its target value, while the average smoke level at the low and middle setpoints were ∼17% larger than their target values.

Table 1
Target operating conditions for the EGR coolers. Standard deviations are in parentheses.

Factor	Low	Midpoint	High
A. EGR Rate (g/s)	83.3 (4.97)	118 (4.07)	152.8 (9.05)
B. EGR Inlet Gas Temperature (°C)	350 (17.5)	450 (11.5)	550 (27.5)
C. Coolant Temperature (°C)	85.0 (1.39)	92.5 (0.676)	100 (1.72)
D. Smoke Level (FSN)	0.500 (0.186)	1.25 (0.109)	2.00 (0.147)
E. Hydrocarbon Concentration (ppm)	25.0 (11.0)	50.0 (4.10)	75.0 (8.69)

The low and high setpoints of 85 °C and 100 °C for the coolant temperatures were selected to reflect typical coolant temperatures found in heavy-duty diesel engines [2]. Because, these temperatures are significantly higher than the dew point for water in the exhaust, which is approximately 40 °C, no condensation of water vapor is expected to occur during fouling [20]. This is confirmed by previous studies which have found that coolant temperatures of 40 °C or below are necessary for the condensation of water [21]. Because of this, the influence of the moisture content in the exhaust gas on the deposit layer thickness is not examined in this investigation.

A five factor, three level fractional factorial design-of-experiments required 20 coolers to test all combinations. As the decrease in performance from fouling exhibits asymptotic behavior, the coolers were run until the effectiveness and pressure drop stabilized (typically 40–70 h). Then, they were allowed to cool down to room temperature and then run for an additional few hours to measure the change in effectiveness due to shut down. High HC could not be achieved with high EGR inlet gas temperatures due to the burning of the HC prior to entering the cooler.

Each cooler had 12 oblong tubes bundled in a 6 by 2 pattern all inside a shell that contained the coolant. Each tube was 48 cm long, 4.4 cm tall and 0.76 cm wide. There were 20 fins inside each tube spaced ∼0.2 cm apart from one another. Along the flow direction, the fins formed a sinusoidal wave with a wavelength of 1 cm and a peak-to-peak amplitude of ∼0.13 cm. All the fins were in phase with one another which resulted in a constant fin spacing down the cooler length. A diagram of cooler tube is shown in Fig. 1.

Following testing, a single tube from the center of each cooler was extracted and sectioned into 25 1.9-cm long segments. A metallographic mount of one section near the inlet of each cooler was prepared by first immersing the sample in epoxy without pulling a vacuum. After the epoxy had set, a few millimeters of material were removed by grinding and then a second epoxy setting, this time under vacuum, was performed. This two-stage procedure reduced disturbances to the deposit while still providing a dense epoxy mount. The sample was then polished using diamond paste with a 1 μm particle size. The epoxy contained a fluorescent dye, which greatly increased the contrast between the deposit and the epoxy thereby allowing the deposit thickness to be measured. Images were acquired using a Keyence VHX optical microscope in dark-field mode which illuminated the polished surface from the side. The software program ImageJ was used to analyze the resulting images to determine the deposit thickness.

Epoxy will tend to collapse the deposit structure which can have a porosity of >95% [4] so this method cannot be used to measure the as-received deposit thickness. This method can, however, be used to compare the relative location of deposit and thus how the cooler geometry impacts deposition. In order to measure the true deposit thickness and how it varies across a sinusoidal fin,