

Removal of EGR Cooler Deposit Material by Flow-Induced Shear

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ABSTRACT

A number of studies have identified a tendency for exhaust gas recirculation (EGR) coolers to foul to a steady-state level and subsequently not degrade further. One possible explanation for this behavior is that the shear force imposed by the gas velocity increases as the deposit thickens. If the shear force reaches a critical level, it achieves a removal of the deposit material that can balance the rate of deposition of new material, creating a stabilized condition. This study reports efforts to observe removal of deposit material in-situ during fouling studies as well as an ex-situ removal through the use of controlled air flows. The critical gas velocity and shear stress necessary to cause removal of deposit material is identified and reported. In-situ observations failed to show convincing evidence of a removal of deposit material. The results show that removal of deposit material requires a relatively high velocity of 40 m/s or higher to cause removal. The resulting shear stress within the deposit is 0.03 to 0.045 kPa. The high velocity needed also results in a high pressure drop across the cooler which makes removal using a purely shear-based difficult in practical engine systems. High flow rate cases in the in-situ experiments did not show evidence of removal even though the velocities were estimated to be high enough; this finding suggests that material removal is not the dominant phenomenon that leads to stabilization. Rather, a combination of shear forces and reduced attractive forces between incident particles and the deposit surface is proposed that results in a lower adherence of incident particles to the deposit, limiting its growth.

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INTRODUCTION

Fouling in EGR Coolers

Cooled EGR has become a mainstay in NO_x emissions control in modern diesel engines and is emerging as a means of improving fuel efficiency in near-term gasoline engines. As has been reported previously by many authors, EGR coolers in diesel applications experience fouling caused by deposition of particulate matter (PM) and semi-volatile species that may include hydrocarbons (HCs), acids, and water within the heat exchanger gas pathways depending upon the operational conditions of the engine system [1,2,3,4,5,6]. The fouling layer that results most often presents a high resistance to heat transfer, and thus decreases the effectiveness of the EGR cooler in its function of reducing the EGR gas temperature.

Studies have shown that in some cases, the fouling process appears to proceed to a steady condition, after which additional effectiveness loss is not observed [7]. This phenomenon is not well-understood, since the existence of a temperature gradient within the gas flow should result in

continuing thermophoretic deposition of soot and further degradation in the thermal performance of the cooler. One possible explanation for this situation is the existence of a critical shear force at which deposit material can be removed at a rate equivalent to the rate of thermophoretic deposition, thus imposing a force balance leading to stabilization of the deposit thickness.

As deposition progresses and the deposit layer grows thicker, the gas velocity increases as a result of the reduction in the cross sectional area of the tube as well as due to a density effect imposed by the reduction in heat transfer. The relative magnitudes of these changes are shown in Figure 1.

Velocity increases as a second-order function of the increase in deposit thickness; the density impact on gas velocity is a linear function. The effect of flow area reduction alone can increase gas velocity more than 50% and is higher when the additional effect of the temperature increase is considered. The significant increases in velocity posed by fouling naturally lead to a hypothesis that stabilization is reached when the velocity-induced shear begins to remove deposit material, eventually balancing the deposition process.

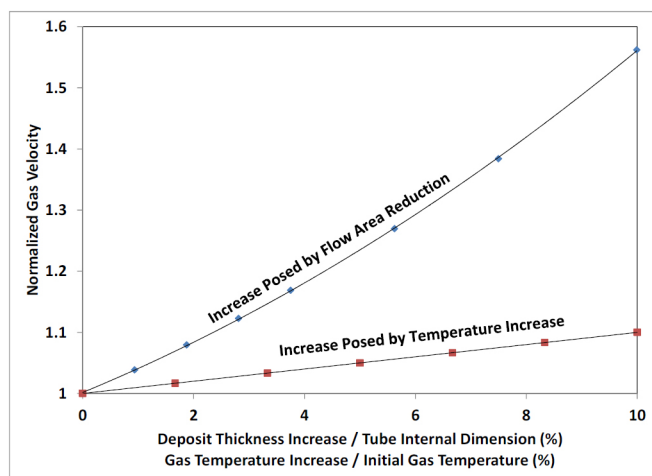


Figure 1. Effects of gas temperature and deposit thickness increases on gas velocity.

Wall Shear Stress, Pressure Drop, and Velocity

The pressure drop for a given length of tube and the shear force sustained at the interface between the deposit layer and the gas flow increases as a result of the increasing gas velocity. The relationship between pressure drop and wall shear stress in a horizontal tube depends both on the length of tube as well as the effective internal diameter as shown in equation 1 [8].

$$\tau_w = R \frac{\Delta P}{\Delta L}$$

Equation 1

This relationship is very useful in relating a measured pressure drop (ΔP) to the wall shear stress (τ_w). In this case, R corresponds to the effective radius at which the gas flow and the deposit surface meet and ΔL is the length of the tube over which the pressure drop was measured. Predicting the pressure drop associated with a given fouling state is more complicated, and depends (among other things) on Reynolds' number for the conditions being investigated. The Blasius correlation relating pressure drop to velocity in low Reynoldsnumber turbulent flow regimes follows as equation 2 [8].

$$\Delta P \approx 0.158 L \rho^{\frac{3}{4}} \mu^{\frac{1}{4}} d^{-\frac{5}{4}} V^{\frac{7}{4}}$$

Equation 2

In this equation, the density (ρ) and the viscosity (μ) have exponents less than unity, meaning that they have less impact than other factors. The two most significant factors are the diameter (d) and velocity (V). If the other factors are held constant, the pressure drop across the tube increases in proportion to the velocity raised to a power of 1.75.

Engine-Based Particulate

Particulate matter emitted from engines takes the form of chain aggregates made up of primary particles. Although diesel primary particles are often quite small (about 30 nm in diameter) and somewhat uniform, aggregates are considerably larger and highly fractal [9].

Defining a diameter (or other characteristic physical dimension) for the aggregates is difficult because of their highly nonuniform geometries. The electrical mobility diameter and the aerodynamic diameter are two common metrics used to characterize the size of the agglomerates. These diameters are not a physical size, but rather an equivalent size based on the response of the particle to electrical and aerodynamic forces, respectively [10]. Thus, although particle aggregate size is often reported as a diameter, aggregates are anything but spherical. Aggregates made of tens of primary particles are often between 50 - 100 nm in terms of their electrical mobility diameters. Aggregates in this size range are generally regarded as having essentially zero mass in terms of momentum effects in gas flows; that is, they behave much like the gas molecules themselves. Tractable means for calculating the electrical mobility or aerodynamic response for a given aggregate physical geometry do not presently exist as such analyses are computationally intensive and would need to be completed for a very large range of potential aggregate geometries.

To complicate matters further, aggregates often have adsorbed chemical species that are dependent on engine conditions both in terms of their mass and speciation, have electrical charges, and have chemical bonds [9,10,11]. These characteristics result in deposits that behave significantly differently from those composed of spherical objects.

Several studies (including studies by the authors) have observed that increasing gas velocities lead to lower rates of deposition of particulate in the EGR cooler tubes. [1,12,13] Some of these studies have suggested that particles are removed by high velocities, leading to the lower deposition. [12,13] However, it is important to note that these studies identified the velocity dependence through its impact on the measured characteristics of the deposit, not by direct observation of particles being removed from the deposit and re-entrained in the flow. The authors suggest that the difference between deposit material removal and the failure of incident particles to become firmly attached to the deposit to begin with is an important distinction in terms of explaining the observed tendency of EGR coolers to foul to a stable condition.

EXPERIMENTAL SETUP

This study focused on the use of surrogate EGR cooler tubes that were made up of a section of square stainless tubing surrounded by a water jacket. These tubes were housed in an experimental apparatus that extracted EGR gases from the engine to support controlled studies of fouling. The tubes were 317.5 mm in length, with an external

dimension of 6.4 mm and a wall thickness of 0.51 mm. The use of surrogate tubes allowed for removal of the tubes from the experimental apparatus so that measurements including deposit mass, deposit thickness, and so on, could be conducted.

The experimental apparatus allowed four surrogate tubes to be fouled simultaneously. The sampling apparatus provided flow control using critical flow orifices as well as temperature measurements for each tube independently. A heated and cooled circulator was incorporated to provide an independent, adjustable source of coolant for the tubes. The sampling apparatus was connected to the engine by means of heat-traced stainless tubing. In this way, the engine operational conditions provided control of the pressure in the surrogate tubes, and established the hydrocarbon (HC) and particulate matter (PM) concentrations in the gases being supplied to the surrogate tubes. The heat tracing of the connecting lines allowed tailoring of the gas temperature at the inlets to the surrogate tubes.

The experimental apparatus was connected to a MY 2008 6.4-liter V-8 diesel engine from a Ford Superduty pickup truck. This engine features a high-pressure common-rail fuel injection system with piezo-electric fuel injectors. The engine is turbocharged and is equipped with two sequential EGR coolers. The experimental apparatus connected to the engine in the high-pressure portion of the exhaust manifold, upstream of the EGR coolers and EGR catalyst. In this way, the experimental apparatus experiences the same exhaust gas makeup and pressure as the EGR coolers on the engine. The fouling conditions for the tubes fouled in the experiments reported in this paper included a 90 °C coolant temperature, 375 °C gas inlet temperature, 50 PPM or lower (as C₁) hydrocarbon concentration, and a filter smoke number (FSN) of 1.5. The exhaust gas hydrocarbon content and pressure were controlled by setting the engine speed and torque with a dynamometer. The engine EGR rate was adjusted during experiments to maintain the FSN at a nearly constant level. The gas mass flow rate varied depending on the experiment, and is detailed further below.

RESULTS

In-Situ Deposit Removal Studies

The first experiments focused on an 8-hour period of tube fouling, followed by a 2-hour period during which the exhaust gases were directed through a particle filter to remove the particles prior to entering the surrogate tubes. This experiment was conducted to examine the fouling resistance data for evidence of a significant removal of the deposit, which would cause the fouling resistance to decrease, rather than continue to increase. This method is an indirect observance of particle removal, since the particle removal is observed through its influence on fouling resistance. During this experiment, two tubes were fouled at a nominal flow rate of 0.049 kg/min with two tubes fouled at 0.073 kg/min simultaneously. Figure 2 shows the average fouling resistance

and tube outlet pressure trends for the tubes during the fouling and filtered portions of the experiment. The fouling resistance increases as fouling proceeds during the 8-hour fouling period. Perturbations in the fouling resistance trends correlate with small pressure fluctuations, indicating that the changes in fouling resistance are likely due to small changes in gas mass flow rate. The pressure fluctuations were associated with adjustments to the engine EGR rate that were necessary to keep the FSN nearly constant for an extended period.

After 8 hours, the exhaust gas was switched to flow through the particle filter, creating a PM-free exhaust gas flow that was at the same temperature. The gas mass flow rate through the tubes dropped marginally due to the pressure decrease associated with the particle filter upstream of the tubes. The gas mass flow rate thereafter continued to decline slowly as a result of PM buildup in the filter. Upon switching to PM-free flow, the fouling resistance was noted to stop increasing and assume a nearly steady value. Minor reductions in the fouling resistance were noted as the pressure dropped due to the increasing PM loading in the particulate filter, but these were attributed to pressure differences, not to removal of deposit material. Hence, the differences noted in fouling resistance during the 2 hours of PM-free flow are largely, if not entirely, explained by the mass flow rate change and fail to provide convincing proof that a significant removal of the deposit has been observed.

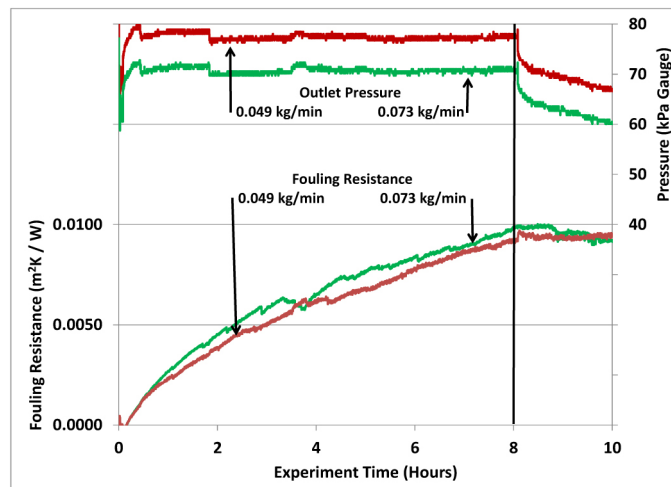


Figure 2. Fouling resistance and pressure trends from in-situ removal experiment.

A second set of experiments was conducted using periodic flow rate changes during fouling to examine whether this condition would provide a semi-continuous removal of deposit material, thus allowing the effectiveness to decline less rapidly than has been observed for steady-flow conditions. Furthermore, if a significant material removal was accomplished, the measured mass of the deposit would additionally provide indirect evidence of the removal. To this end, two tubes were fouled using steady flow conditions of