

Characteristics of Soot Deposits in EGR Coolers

Ho Teng and Gerhard Regner

AVL Powertrain Engineering, Inc.

Copyright © 2009 SAE International

ABSTRACT

Characteristics of soot deposits in the EGR cooler were studied, on basis of which a comprehensive model for soot particle depositions was developed. It was found that the soot deposit may be divided into three characteristic layers: a quasi-crystal base layer formed by nano-particles, an intermediate layer of denser packing of soot particles with meso pores, and a highly porous top layer formed by mechanical interlocking of soot particles. The cooler performance is affected significantly by the top layer of the deposit. Because of their weak contact energy, particles in the top layer and intermediate layers may be removed by the shear force under high EGR flows. The contact energy for the particles in the base layer is much stronger than that in the surface and intermediate layers. The base layer may be removed only with physicochemical methods. Due to the aforementioned characteristics of the soot deposit, behavior of the EGR cooler fouling at the transient engine operation differs from that at the steady-state engine operation. This characterization on the soot deposits in the EGR cooler agrees with experimental observations.

INTRODUCTION

High fuel-injection pressures and high EGR rates are promising strategies for soot and NO_x reductions to meet the US 2010 emission standards for heavy-duty diesel engines. However, these methods are interdependent and tradeoffs must be evaluated. High fuel-injection pressure results in smaller soot particles, which lowers the mass-based soot emission. The number density for the soot particles usually increases with shifting the mean particle size to the small size range as a result of increasing the fuel injection pressure. Smaller soot

particles and a higher number density are the characteristics of the exhaust of the 2010 HD diesel engines. Soot particles within the EGR gas with such characteristics favor the formation of thermophoretic deposits on the wall of the EGR cooler. As a result, the EGR cooler fouling becomes significant for the 2010 HD diesel engines. The increased deposit thickness on the heat transfer surfaces leads to decrease in the effectiveness of the EGR cooler and increase in the flow resistance. Consequently, the cooler performance deterioration due to particulate fouling has an impact on controlling the NO_x emissions.

Degradation in the performance of EGR coolers for HD diesel engines has been studied by many investigators [1-12]. Most of these previous investigations were experimentally orientated and focused on evaluations of the effectiveness for the fouled coolers. Due largely to the complexity in the process of particulate fouling, few studies have been reported on characterization of the soot deposit and modeling the fouling process. A better understanding of the physics for the EGR cooler fouling is needed to mitigate the EGR cooler fouling via controlling the engine operation conditions. To this end, this study investigates the physics for the EGR cooler fouling process and the characteristics of the deposits formed in the EGR cooler.

CHARACTERISTICS OF SOOT DEPOSIT

PARTICULATE DEPOSITION IN EGR COOLER

Building blocks for particulate matter (PM) in the diesel exhaust consists of three types of nano particles (< 50 nm): soot, metallic ash, and sulfate hydrate particles. Soot and metallic ash particles are generated from combustion of diesel fuel and lube oil entered in the

engine cylinder. These solid particles form fine particles (50~1000 nm) through agglomeration or clustering in the early expansion stroke (at $T < 1000\text{ }^{\circ}\text{C}$), with sulfate hydrate particles (at $T < 450\text{ }^{\circ}\text{C}$) and condensed heavy species of unburned hydrocarbons (at $T < 300\text{ }^{\circ}\text{C}$) added to them in the later expansion stroke. Amount of sulfate hydrate varies with the fuel sulfur content and the mass of condensed hydrocarbons, i.e., soluble organic fraction or SOF, varies with the exhaust temperature.

Coarse particles $> 1000\text{ nm}$ also exist in the exhaust. However, they have been reduced significantly as a result of PM reduction. For EGR cooler fouling, only the fine particles with sizes on orders $10^1\sim10^2\text{ nm}$ are relevant [13,14]. Since soot is the dominant content in PM, the dispersed particles in the EGR gas are termed as soot particles in this study. The soot particles suspended in the EGR gas are always subjected to actions from various external forces. The external forces on the soot particles are in four types: 1) the thermophoretic force due to unbalanced molecular bombardment forces because of the high temperature gradient in the EGR cooler; 2) the gravitational settling force due to the difference in densities of the particles and the EGR gas; 3) the electrostatic force arising from the static charge formed on the particles and the electrostatic field generated by friction between the EGR gas and the wall of the flow channels; 4) the Brownian motion force on particles due to random actions from neighboring other particles. These external forces cause drift of some particles from the main stream. The drift motion of these particles results in particle deposition onto the heat transfer surfaces of the EGR cooler, causing the cooler fouling. Soot particles in the EGR gas have a number density in the range $10^8\sim10^9\text{ particles/cc}$, with the mean particles size on the order 10^2 nm . Particles in this size range are highly dispersive. Under these conditions and the high temperature gradient in the EGR cooler, the thermophoretic force is at least one order of magnitude greater than other external forces [15]. Thus, the deposition of soot particles in the EGR cooler is driven primarily by the thermophoretic force.

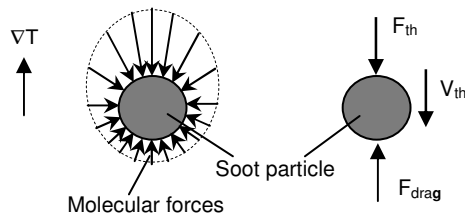


Fig.1 Thermophoretic force on a soot particle.

Thermophoresis is a type of mass transfer of particles due to thermophoretic drift motion. Figure 1 shows the thermophoretic force on a soot particle. In Fig.1, F_{th} and V_{th} are the thermophoretic force and thermophoretic velocity, and F_{drag} is the drag force.

Velocity for the thermophoretic drift motion can be obtained by the force balance over the soot particle as

$$V_{th} = -K_{th} \times (\nu / T) \times \nabla T, \quad (1)$$

where ν is the kinematic viscosity of the EGR, T is the EGR temperature in Kelvin, ∇T is the temperature gradient, and K_{th} is the thermophoretic coefficient. The negative sign in Eq.(1) indicates that the soot particle moves in the direction opposite that of the temperature gradient.

STRUCTURE OF SOOT DEPOSIT

Because thermophoresis is most effective on the nano particles, the nano particles are the first to land on the cooler wall. After a short induction time, these particles form a surface coating. The van der Waals force and weak chemical bonding on the particle surfaces hold the particles together. Due to the interactions with the metallic bonds and charges on the metal surface, these particles form a quasi-crystalline structure [16] after many steps of reorientation and rearrangement. This base layer has a low porosity thus high density and thermal conductivity. After the initial buildup, the deposit on the wall begins to grow. Because soot particles themselves basically have no surface charge [17], the deposit buildup over the base layer is due largely to random packing. Only in the packing close to the base layer, soot particles are held together by the van der Waals force on particle surfaces. The particles on the surface layer of the deposit are held together via mechanical interlock. The deposit above the base layer can be further divided into two sub-layers according to the types of the contact forces: an intermediate layer and a surface layer. The intermediate layer has medium level density and thermal conductivity. The surface layer is a loose layer and may be better viewed as soot clusters connected with mechanical interlock; it has a high porosity and thus low density and thermal conductivity.

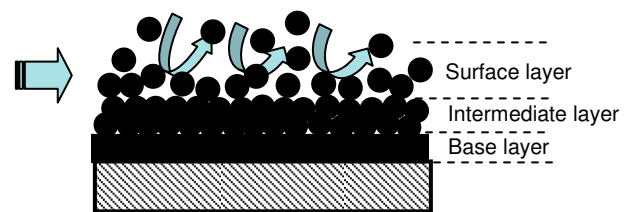


Fig.2 Structure of soot deposit on the EGR cooler wall.

Figure 2 characterizes the soot deposit on the cooler wall. It has a three-layer structure: a dense base layer with micro pores ($< 10\text{ nm}$), a randomly-packed intermediate layer with meso pores ($10\text{-}50\text{ nm}$), and a loose surface layer with macro pores ($> 50\text{ nm}$). This three-layer structure for the deposit was proposed based on our observations and the pore sizes are estimated according to the pore structures for soot particles.

reported by Butler and Mulholland [18]. Due to the high contact energy of the nano particles, a special solvent may have to be used to remove the base layer [19]. The intermediate layer and the surface layer are removable by the shear force under high EGR flows if the corresponding threshold friction velocity [20] can be reached.

CHARACTERISTICS OF SOOT DEPOSIT

Figure 3 shows the surface soot particles collected from a fouled EGR cooler for a HD diesel engine. These particles are soot clusters and they are lighter than water when dry. The surface particles break easily under a shear force. Breakups from these clusters can be airborne as long as the EGR velocity is not too low. The heat transfer characteristics of the soot deposit on the cooler wall are governed primarily by the loose surface layer. Thus, the fouling resistance or the fouling factor (defined as the ratio of the deposit thickness to its thermal conductivity) of the EGR cooler is affected significantly by the behavior of the surface layer.



Fig.3 Soot particles collected from surface layer of deposit.

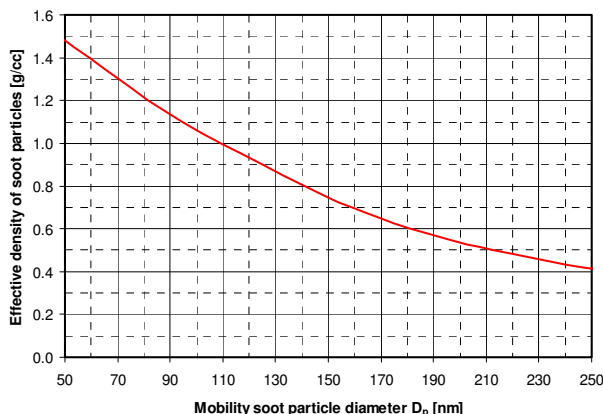


Fig.4 Effective density of soot particles in diesel exhaust.

Figure 4 shows the averaged density for soot particles formed in various engine operation conditions of a HD diesel engine. In Fig.4, the data for the effective

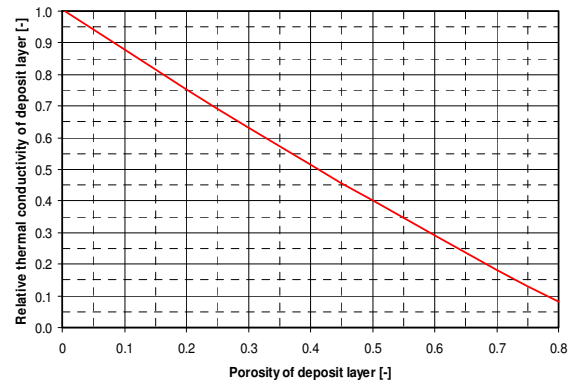


Fig.5 Deposit layer to soot thermal conductivity ratio.

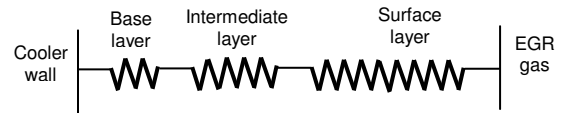


Fig.6 Illustration of heat transfer resistance of deposit layer.

densities represent the average values reported by several investigators [14,21,22]. It is seen that the particle density decreases with increase in the particle size. Figure 5 shows the estimated relative thermal conductivity of the deposit layer, i.e., the ratio of the thermal conductivity of the deposit layer to that of soot [23]. Because the porosity of the base layer is lower than that of the surface layer, the thermal conductivity of the base layer is greater than that of the surface layer. The relative heat transfer resistances for the three layers of the soot deposit are illustrated in Fig.6. The surface layer has the largest heat transfer resistance because it is highly porous and the pores in the deposit are filled with the EGR gas.

The soot particles on the surface layer are in a dynamic balance of deposition and removal. The thickness of the surface layer is variable with changes in the EGR flow condition accordingly. Due to this nature of the surface layer, the fouling factor is not a constant. The cooler fouling is stabilized only relatively, i.e., stabilization is meaningful only for a fixed EGR-cooler inlet condition. Fouling factor for a “stabilized cooler” can be variable under a fixed EGR flow rate: it increases with enhancing the soot particle deposition, e.g., increasing the inlet particle concentration or temperature, and it decreases with reducing the soot particle deposition, e.g., reducing the inlet particle concentration or temperature.

EGR COOLER FOULING MODEL

PARTICULATE DEPOSITION IN EGR COOLER

EGR coolers commonly used in HD diesel engines are basically in two types: the tube-fin type and the tube-