

Particulate Fouling in EGR Coolers

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ABSTRACT

The physical process of particulate fouling in EGR coolers is analyzed in this paper. Various particulate-deposition mechanisms are discussed and an order of magnitude comparison suggests that thermophoresis is the dominant mechanism for the EGR cooler fouling. The EGR temperature at the cooler inlet, the soot particle concentration in EGR, and the EGR mass flow rate are found to be the parameters governing the EGR cooler fouling. The structure for the soot deposit buildup on the cooler wall is also discussed. It is found that the surface layer of the deposit governs the fouling factor. A comprehensive model for soot particle depositions is developed employing heat, mass, and momentum transfer theories for the particle-gas system. The fouling model developed in this study can predict the process of deterioration in the effectiveness. The predictions of EGR cooler fouling are compared with experimental data and good agreement is observed. This indicates that the EGR-cooler fouling model reasonably characterizes the fouling process.

INTRODUCTION

Degradation of the EGR-cooler performance as a result of particulate fouling became an issue when the Tier-2 emission standards for HD diesel engines were phased in [1-6]. However, deterioration in the EGR cooler effectiveness due to fouling was less important for the Tier-2 engines because the EGR coolers were sufficiently large for the EGR flows, thus mitigating effectiveness degradation. The working period for the EGR coolers was reasonably long before a refreshment service was required.

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. 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 characteristic of the exhaust of 2010 HD diesel engines. Soot particles within the EGR gas with such characteristics favor the formation of thermophoretic deposits on the EGR cooler wall. 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 a decrease in the effectiveness of the EGR cooler and an increase in the flow resistance. Consequently, the cooler performance deterioration due to particulate fouling has an impact on the control of the NO_x emissions.

Degradation of the EGR cooler performance for the 2010 HD diesel engines have been studied by many investigators recently [7-10]. Most of the previous investigations were experimentally orientated and focused on evaluations of the effectiveness of the fouled coolers. Due largely to the complexity in the process of particulate fouling, few studies have reported on modeling of the fouling process and prediction of the fouling resistance (i.e., the fouling factor). A better understanding of the physics of 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 of the EGR cooler fouling process and the characteristics of the deposits formed in the EGR cooler.

THEORY FOR EGR COOLER FOULING

FORCES ON SOOT PARTICLES IN EGR GAS

Building blocks for particulate matter (PM) in the diesel exhaust consist of three types of nano particles (< 50 nm generally): soot, metallic ash, and sulfate hydrate particles. Soot and metallic ash particles are generated from combustion of diesel fuel and lube oil entered into the engine cylinder. These solid particles form fine particles (50-1000 nm) through agglomeration or clustering in the early expansion stroke (at $T < 1000$ °C); sulfate hydrate particles (at $T < 450$ °C) and condensed heavy species of unburned hydrocarbons (at $T < 300$ °C) are added to them in the later expansion stroke. The 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 nm) also exist in the exhaust. However, they have been reduced significantly as a result of PM reduction. Thus, the bi-nodal particle size distribution for the pre-2004 HD diesel engines [11] is no longer a characteristic of 2010 HD diesel engines. For EGR cooler fouling, only the fine particles with sizes on the orders 10^1 - 10^2 nm are relevant.

Since soot is the dominant component of 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 kinds of external forces. 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.

The types of external forces on the soot particles can be divided into four groups: 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 of the EGR cooler; 4) the Brownian motion force on a particle due to random actions from other neighboring particles.

Static charges are usually generated by the polar molecules (such as water and some oxygenated hydrocarbons), for which the positive and negative charges are not in balance locally. Non-polar molecules (N_2 , CO_2 and O_2) form up to 95 wt% of the diesel exhaust. Thus, if water and other polar hydrocarbon molecules in the EGR gas are in a superheated state, the electrostatic forces on the soot particles are negligible. Particles sized 10^1 - 10^2 nm are highly dispersive and their motions are only slightly influenced by gravitational forces. Soot particles in the EGR gas

have a number density in the order of 10^8 particles/cc while the number density for molecules (average size ≈ 0.3 nm) in the EGR gas is on the order of 10^{19} molecules/cc. In an environment where the temperature gradient is large, the thermophoretic force is at least one order of magnitude greater than that of the Brownian motion force [12]. Thus, the deposition of soot particles in the EGR cooler is driven primarily by the thermophoretic force.

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 of the thermophoretic drift motion can be calculated using the force balance over the soot particle,

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

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 from a high temperature location to a low temperature location.

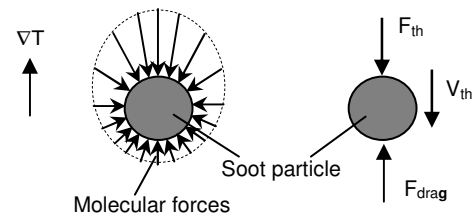


Fig.1 Thermophoretic force on a soot particle.

THERMOPHORETIC DEPOSITION IN EGR COOLER

Consider an EGR cooler with multiple flow channels in parallel. Because all flow channels are in parallel, only a single channel needs to be selected to study the cooler fouling. The channel selected (Fig.2) is modeled as a cylindrical tube in the hydraulic diameter sense, with

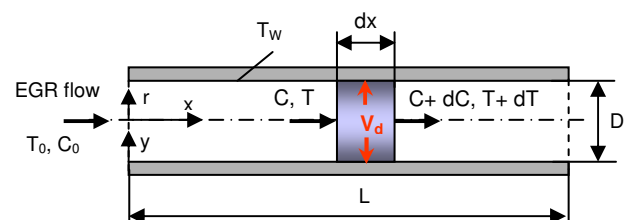


Fig.2 Model for soot deposition in EGR cooler.

internal diameter = D , length = L , and wall temperature = T_w (constant). At the EGR cooler inlet, the EGR temperature = T_0 and the soot concentration = C_0 . It is assumed that $T_0 \gg T_w$ and thermophoresis governs drift motions of soot particles in the EGR cooler. Thus, the particle deposition velocity V_d may be approximated by the thermophoretic velocity V_{th} , i.e., $V_d \approx V_{th}$.

The EGR flow is assumed to be steady state and have fully developed turbulent flow, with a mean EGR velocity in the channel U . In the dx section of the channel (shown in Fig.2), the rate of the soot particle deposition onto the wall is equal to the rate of change in the soot particle concentration C over the dx distance:

$$-\frac{\pi}{4} D^2 U dC = C V_d \pi D dx \quad (2)$$

In Eq.(2), the negative sign is due to $dC < 0$. Rearranging Eq.(2) and noting that $V_d = V_{th}$, yields:

$$\frac{dC}{C} = \frac{4K_{th} \nu}{UD} \frac{1}{T} \frac{dT}{dr} dx \quad (3)$$

The rate of heat transfer to the cooler wall in the dx section is equal to the rate of change in the EGR enthalpy:

$$-\frac{\pi}{4} D^2 U \rho C_p dT = h \times (T - T_w) \times \pi D dx \quad (4)$$

ρ and C_p are the EGR density and heat capacity, respectively, and h is the heat transfer coefficient. Rearranging Eq.(4) leads to

$$\frac{dT}{T - T_w} = -\frac{4h}{\rho C_p U D} dx \quad (5)$$

The solution of Eq.(5) is

$$T = T_w + (T_0 - T_w) \times \exp\left(-\frac{4hx}{U\rho C_p D}\right) \quad (6)$$

Since the flow in the EGR cooler is turbulent, the changes in the concentration and temperature take place only in a thin layer near the wall. The temperature gradient in this boundary layer can be determined by:

$$\frac{dT}{dr} = -(h/k_g) \times (T_0 - T_w) \times \exp\left(-\frac{4hx}{U\rho C_p D}\right) \quad (7)$$

The soot particle fouling can be characterized by the deposition efficiency η_d defined in the following:

$$\eta_d = 1 - \frac{C_L}{C_0} \quad (8)$$

C_L is the soot particle concentration at the cooler outlet. Solving Eq.(3), and combining it with Eq.(7), yields:

$$\eta_d = 1 - \left[\frac{T_w}{T_0} + \left(1 - \frac{T_w}{T_0}\right) \times \exp\left(-4St \frac{L}{D}\right) \right]^{Pr K_{th}} \quad (9)$$

Pr is the Prandtl number for EGR and St is the Stanton number. For fully developed turbulent flows, $St = 0.023 Re^{-0.2} Pr^{-0.6}$, where Re is the Reynolds number, the thermophoretic coefficient can be expressed as [13]:

$$K_{th} = 2C_s \frac{(k_g/k_p + C_t K_n) \times [1 + K_n \times (1.2 + 0.41 \times e^{-0.88 K_n})]}{(1 + 3C_m K_n) \times (1 + 2k_g/k_p + 2C_t K_n)} \quad (10)$$

k_g and k_p are the thermal conductivities of the EGR gas and the soot particle, $K_n = 2\lambda/d_p$ is the Knudsen number, λ is the mean free path for the exhaust molecules, and d_p is the soot particle diameter; $C_s = 1.147$, $C_t = 2.2$; $C_m = 1.146$.

For soot particles sized $10^1 \sim 10^2$ nm and EGR temperatures > 300 °C, the value of the thermophoretic coefficient K_{th} falls into a narrow range from 0.5 to 0.6 and $Pr \approx 0.7$ for the EGR gas. Thus, the influences of K_{th} and Pr on η_d are limited. Equation (9) reveals that the soot particle deposition is primarily governed by T_w/T_0 , Re , and L/D . For a given EGR cooler, the difference between the EGR inlet temperature T_0 and the wall temperature T_w is the driving force for the particulate fouling and the Reynolds number Re is a resistance to the fouling.

EGR COOLER FOULING PROCESS

The deposition efficiency η_d characterizes the EGR cooler fouling only qualitatively. To characterize the EGR cooler fouling quantitatively, the process for the deposit buildup on the heat transfer surfaces of the EGR cooler must be studied. Figure 3 describes the deposit buildup model, which is an extension of the model described in Fig.2 with the deposit buildup on the cooler wall included. It is assumed that the processes coexist for the soot particle deposition onto the cooler wall and the deposit removal from the cooler wall.

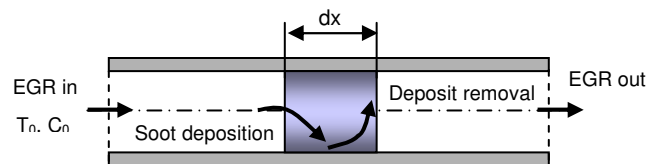


Fig.3 Model for deposit build-up on the cooler wall.