

A Semi-Empirical Model for Predicting Pressure Drops of Fouled EGR Coolers

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ABSTRACT

The performance of an EGR cooler is influenced significantly by particulate fouling in the cooler. As a result of fouling, a highly-porous soot deposit layer is formed in the EGR cooler. This deposit layer not only causes a decrease in the cooler effectiveness but also an increase in the EGR pressure drop over the cooler. Increasing the EGR cooler pressure drop reduces the driving force for the EGR flow under a given differential pressure across the engine. Thus, the EGR cooler fouling has a big impact on the control of the engine-out NO_x emissions. In this paper, a semi-empirical model is developed for predicting pressure drops of fouled EGR coolers. Based on this model and the particulate fouling model developed previously by the author, the process is analyzed for the pressure drop increase with building up of the soot deposit in an EGR cooler. The predicted pressure drops for the fouled coolers agree well with the experimental data for both tube-winglet type and tube-fin type EGR coolers.

INTRODUCTION

High fuel-injection pressures effectively reduce sizes of soot particles formed during the combustion process thus lower mass-based soot emissions. The number density for soot particles in the engine exhaust usually increases when the mean particle size shifts to the small size range. Smaller soot particles and a higher number density are the characteristics of the exhaust from the 2010 heavy-duty (HD) diesel engines. To meet the US-2010 emission regulations for HD diesel engines, high rates of the exhaust gas recirculation (EGR) must be applied for reducing in-cylinder NO_x formation. Small particles with a high number density in the EGR gas favor 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 soot deposit

formed on the heat transfer surfaces of the EGR cooler is highly porous and its thickness is on order of 10² μm. It causes not only deterioration in the cooler effectiveness but also a considerable increase in the EGR-flow resistance. In-house EGR cooler fouling studies have shown typically a decrease in the cooler effectiveness of up to 30% and an increase in the EGR pressure drop about 2 times when the cooler performance became stabilized. The decrease in the effectiveness and increase in the pressure drop of the EGR cooler consequently led to increase in the charge temperature and decrease in the engine's EGR drivability, causing a huge impact on controlling the engine-out NO_x emissions.

The process of particulate deposition on the wall of the EGR cooler and its influence on the effectiveness of the EGR cooler had been investigated by the present author and coworkers [1,2,3] and many other investigators [4,5,6,7,8,9,10,11,12,13,14]. However, these investigations provide only limited information on the relationship between the cooler fouling and the increase in the EGR pressure drop. It is difficult to characterize the performance of a fouled EGR cooler without knowledge of the impact on changes in the EGR flow resistance due to the cooler fouling. Thus, this study focuses on better understanding of the influence on the resistance to the EGR flow due to particulate deposition in the EGR cooler.

PARTICULATE DEPOSITION ON THE WALL OF EGR COOLER

PARTICULATE FOULING IN EGR COOLER

The dispersed particles in the EGR gas can be classified into three major particle systems: soot particles, metallic ash particles, and sulfate hydrate particles. The mass of PM in the EGR gas is dominated by the soot particle system; thus, the

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dispersed particles are termed as soot particles for simplicity in this study. The soot particles suspended in the EGR gas are always subjected to actions from various external forces, with the thermophoretic force being the dominant [3]. The drift motion of the soot particles due to thermophoresis results in particulate deposition onto low-temperature surfaces of the EGR cooler, causing the cooler fouling. Soot particles in the EGR gas have a number density in the range $10^7 \sim 10^9$ particles/cc, with the mean particles size on the order of 10^2 nm. The greater the EGR temperature gradient in the cooler and the higher the particle number density are, the stronger the driving force for particle deposition will be [2]. 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 Figure 1, F_{th} is the thermophoretic force, V_{th} is the 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

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

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 same direction that the heat flux flows. The drift motion of the soot particles is not affected by SOF. However, SOF may have a significant influence on the structure of the deposit because it changes the contact force holding the particles together in the deposit.

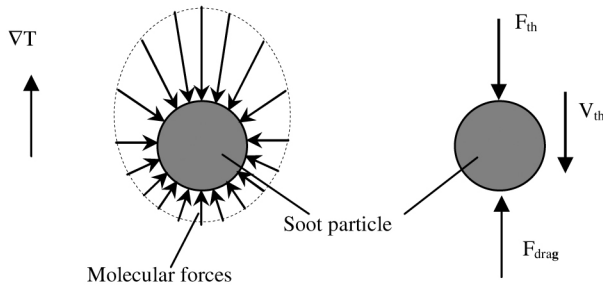


Figure 1. Thermophoretic force on a soot particle.

An analysis on particulate deposition in the EGR cooler was reported previously by Teng and Regner [2]. In their study, the EGR cooler is modeled as a heat exchanger with multiple identical EGR flow channels in parallel; thus, only a single channel needs to be selected for the fouling study. Figure 2 shows the channel under investigation which is a cylindrical tube in the hydraulic diameter sense, with the internal diameter = D , length = L , and wall temperature = T_w . At the EGR cooler inlet, the EGR temperature = T_0 ($T_0 \gg T_w$) and the soot concentration = C_0 . Because the thermophoresis

governs drift motions of soot particles in the cooler, the particle deposition velocity V_d may be approximated by the thermophoretic velocity V_{th} , i.e., $V_d \approx V_{th}$.

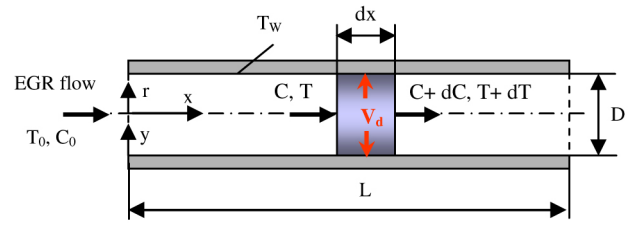


Figure 2. Model for soot deposition in the EGR cooler.

The particulate fouling in the EGR flow can be characterized by the fouling resistance (more often termed as fouling factor) and the fouled-cooler effectiveness [2]:

Fouling factor for a stabilized EGR cooler R_f^* :

$$R_f^* = \frac{K_1 C_s}{K_2 k_d U} \times \left\{ 1 - \left[\frac{T_w}{T_0} + \left(1 - \frac{T_w}{T_0} \right) \exp \left(-4St \frac{L}{D} \right) \right]^{\text{Pr} K_{th}} \right\} \quad (2)$$

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

Effectiveness of a fouled EGR cooler ε_f :

$$\varepsilon_f = \left\{ 1 - \exp \left[- \frac{4 \times (L/D) \times (1 + C)}{1 + R_f \times K} \times \frac{K/G}{C_p} \right] \right\} / (1 + C) \quad (4)$$

In the above equations, K_1 and K_2 are cooler structure related constants, C_s is the soot mass concentration in the EGR gas, k_d is the thermal conductivity of the deposit, and U is the main EGR velocity; Pr is the Prandtl number for the EGR gas and St is the Stanton number; G is the EGR mass velocity or mass flux, K is the overall heat transfer coefficient for the clean cooler, and the heat capacity rate $C = (\dot{m}C_p)_{\text{EGR}} / (\dot{m}C_p)_{\text{coolant}}$; the constants in the thermophoretic coefficient K_{th} expression are: k_g and k_p the thermal conductivities of the EGR gas and the soot particle, $K_n = 2\chi/d_p$ the Knudsen number, χ the mean free path for the exhaust molecules, d_p the soot particle diameter, $C_s = 1.147$, $C_t = 2.2$ and $C_m = 1.146$ [15]. Equations (2) and (4) characterize the thermal performance for a fouled EGR cooler. The details about the EGR cooler fouling model and comparison of model predictions with measurements can be found in [2].

SOOT PARTICLE BUILDUP ON THE WALL OF EGR COOLER

An alternative expression for the fouling factor is

$$R_f = \delta/k_d \quad (5a)$$

where δ is the thickness of the deposit layer. The fouling factor can be given by Eqs.(2) and (4). If the thermal conductivity for the deposit layer k_d is known, then the thickness of the deposit layer δ can be given as

$$\delta = R_f \times k_d \quad (5b)$$

The soot deposit buildup on the wall of the EGR cooler has a highly porous structure. The reported specific area for the soot clusters in the exhaust is in the range 30~50 m²/g [15,16,17,18]. The variation in the specific area is due to differences in particle size distribution. The larger the particles sizes are, the greater the sizes of pores in the clusters are, and therefore the lower the effective density and thermal conductivity of the soot clusters will be. To characterize the thermal conductivity for the deposit layer, the thermal conductivities for both the solid frame and the fluid (here, the EGR gas) in the pores must be considered. The thermal conductivity for the soot clusters k_p may be expressed as [19]

$$k_p = (1-\phi)k_s + \phi k_f \quad (6)$$

where ϕ is the porosity, k_s and k_f are the thermal conductivities for the solid frame and gas in the pores. Equation (6) may be rewritten as

$$\frac{k_p}{k_s} = 1 + \phi \left(\frac{k_f}{k_s} - 1 \right) \quad (7)$$

Ciro et al. [20] suggested that the dependence of the relative thermal conductivity k_p/k_s on ϕ be expressed in the following relationship:

$$\frac{k_p}{k_s} = (1-\phi)^{1.5} + \phi^{0.25} \frac{k_f}{k_s} \quad (8)$$

For the soot clusters, k_f is the thermal conductivity of the exhaust gas and k_s may be estimated using the thermal conductivity for graphite [21] with some correction when the thermal conductivity of the primary soot particles is not available. The relative thermal conductivity described by Eq. (8) is plotted in Figure 3.

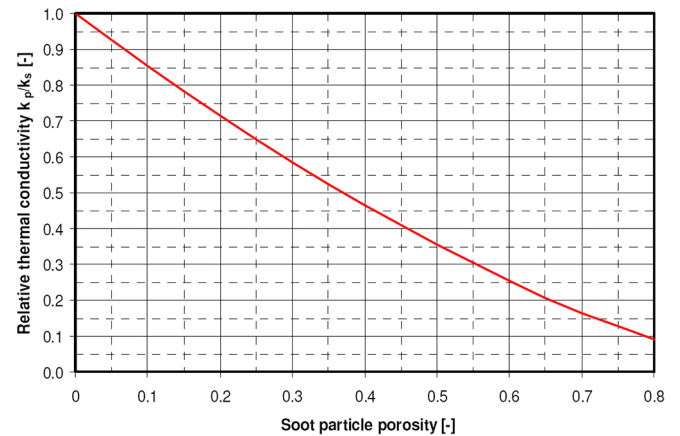


Figure 3. Relative thermal conductivity of soot particle.

Because the porosity of the soot deposit layer is often not available, it is not easy to apply the relative thermal conductivity relationship given in Figure 3. For a porous medium with the pores filled with a gas, its effective density and thermal conductivity are related. It is more convenient to predict the thermal conductivity based on the density of the deposit layer, which can be measured easily. Figure 4 shows a relationship between the thermal conductivity and the effective density of the soot particles. This relationship was developed by the present author based on the thermal conductivity data reported in the available literature for the soot clusters.

Although the overall structure of the soot deposit differs from the soot clusters, their local structures are similar because the soot clusters are the building blocks for the soot deposit. The reported values of the thermal conductivity for soot vary with investigators. Kaupp [22] suggested that the estimation of the thermal conductivity of the soot deposit may be taken as 1.0 W/m.K. The thermal conductivity of the soot deposit reported by Lance et al. [23] was 4.1×10^{-2} W/m.K. The difference between the two reported values is due largely to the difference in the porosity of the deposit. The thermal conductivity of the EGR gas is also on the order 10^{-2} W/m.K; this indicates that the EGR gas in the pores of the soot deposit has a significant influence on the thermal conductivity of the soot deposit. If the deposit may be assumed to have a structure formed with random packing of the soot particles (clusters), the thermal conductivity for the soot deposit should be on the order $10^{-2} \sim 10^{-1}$ W/m.K. In case that the experimental data are unavailable, the thermal conductivity for the deposit may be estimated from Figure 4. Figure 5 compares the measured effectiveness with the model prediction for a tube-fin EGR cooler on a HD diesel engine operated at medium load and 60% rated engine speed, which represents a common engine load condition for mobile applications. The corresponding deposit buildup predicted by the fouling model is also presented in Figure 5. In Figure 5,