

The Effects of Temperature, Shear Stress, and Deposit Thickness on EGR Cooler Fouling Removal Mechanism - Part 2

Hyunki Sul, Taehoon Han, Mitchell Bieniek, and John Hoard
University of Michigan

Chih-Kuang Kuan and Daniel Styles
Ford Motor Company

ABSTRACT

Exhaust gas recirculation (EGR) coolers are used on diesel engines to reduce peak in-cylinder flame temperatures, leading to less NO_x formation during the combustion process. There is an ongoing concern with soot and hydrocarbon fouling inside the cold surface of the cooler. The fouling layer reduces the heat transfer efficiency and causes pressure drop to increase across the cooler. A number of experimental studies have demonstrated that the fouling layer tends to asymptotically approach a critical height, after which the layer growth ceases. One potential explanation for this behavior is the removal mechanism derived by the shear force applied on the soot and hydrocarbon deposit surface. As the deposit layer thickens, shear force applied on the fouling surface increases due to the flow velocity growth. When a critical shear force is applied, deposit particles start to get removed. In this study, a 1-D model is developed to predict effectiveness drop and fouling layer distribution across the cooler. To model the removal mechanism, experiments described in Part 1 of this paper were conducted. Removal of particles was measured by blowing compressed air in various conditions through the fouled tube from the shell-in-tube type EGR cooler rig. A deposit removal regression equation was developed using the blow out experiment data, which was incorporated into the model. The resulting model showed good correspondence with the experimental data, indicating that removal mechanism improves the prediction of modeling. For the first time, the new model with the empirically derived removal function is able to predict the trend of thermal effectiveness stabilization observed in experiments.

CITATION: Sul, H., Han, T., Bieniek, M., Hoard, J. et al., "The Effects of Temperature, Shear Stress, and Deposit Thickness on EGR Cooler Fouling Removal Mechanism - Part 2," *SAE Int. J. Mater. Manf.* 9(2):2016, doi:10.4271/2016-01-0186.

INTRODUCTION

The build-up of deposit layers inside EGR coolers is a serious issue because it reduces heat transfer performance, which decreases the amount of NO_x reduction that can be achieved by using EGR. The fouling layer also increases pressure drop across the cooler and degrade the engine efficiency. During sufficiently long deposition periods, the thickness of fouling layer asymptotically reaches to a stabilized value. A large number of studies have investigated the fouling phenomenon experimentally or by using a steady state simulation model.

Hoard et al. [1] reviewed the literature on automotive EGR cooler fouling and explained what deposits are and how they occur. Abd-Elhady et al. [2] gathered research about fouling mechanisms and analysis of the deposit layer. Zhang et al. [3] empirically characterized the six-tube EGR cooler performance and concluded that the fouling caused significant impact on thermal resistance increment and pressure drop. They also observed the entrance diameter reduction by at least 33% during the test. Particle deposition was experimentally measured using monodisperse NaCl particles

under laminar and turbulent flow conditions in Tsai et al. [4]. These deposit layer investigation has attracted an effort to conduct research to mitigate the fouling over the last several years. [5,6,7,8].

There have been several studies that have tried to investigate the main force of the fouling and attempted to simulate it. Abarham et al. [9] compared various types of forces that can cause soot deposition and concluded thermophoresis is the dominant one. Thermophoresis is the force due to the temperature gradient between hot exhaust gas and cold cooler surface. Housiadas and Drossinos [10] developed steady state model to predict thermophoretic particle deposition in laminar and turbulent circular pipe flow. Previous empirical equations regarding thermophoretic deposition showed good agreement with their experimental results. It was also shown that Talbot's formula [11] representing thermophoretic deposition is more accurate than Waldmann's free molecular formula [4].

Hoard et al. [12] analyzed the fraction of the deposit hydrocarbons such as C₁₀-C₁₇ alkane, C₁₈-C₂₄ alkane, and light or heavy aromatics. Prabhakar et al. [13] and Lance et al. [14] also inspected the chemical

composition of the cooler deposit layer. Based on the studies of chemical composition and thermophoretic force, 1-D model of fouling mechanism was developed.

Abarham et al. simulated a 1-D transient tube flow in the cooler considering thermophoresis and HC condensation. The model implemented thermophoretic velocity in the concentration equation to describe a particle drift from the hot exhaust gas to cooled heat exchanger wall. Effective diameter and deposit surface temperature change due to fouling was numerically calculated and considered in the next time step of parameters calculation. [15] In their further simulation, condensation of a wide range of hydrocarbon molecules was modeled. [16] Results showed reasonable consistency with the experimental results.

A potential explanation of the stabilizing effectiveness drop is the particle removal inside the cooler. Abarham et al. [17] explored the removal of layer as a result of water condensation. Lance et al. [18] found a deposit spallation in a high flow rate condition due to intense shear stress. Sluder et al. [19] conducted removal studies with an exsitu experiment. They blew room temperature air through the deposited surrogate tube and measured the removal rate and size of the particles blown out from the tube. The result showed that very high flow rate, more than 40m/s, was required for particle removal.

Teng [20] developed the semi-empirical model to predict pressure drop across the cooler and demonstrated agreement with tube-winglet type and tube-fin type EGR cooler experimental data. He estimated the pressure drop based on the thickness of the soot deposit build up. Teng also defined the deposit removal related to the structure and the contact energy of the soot particles in the deposit. His model predicted the process of cooler effectiveness deterioration very well [21].

There are several studies discussing soot particle fouling model in heat exchangers. Many articles available in literature explain the deposition of particles and its physics but there is no published article in model that incorporates the removal mechanism based on experimental data. In this paper, we analyzed the regression equation derived from the experiment in Part 1 and updated the previous model for soot deposition [16] with removal mechanism. Experimental measurements are used to derive the regression equation which represents the particle removal as a function of pressure drop, temperature, and thickness. Model predictions of cooler thermal effectiveness, total mass gain, and pressure drop were compared to the experimental data.

ANALYSIS OF REGRESSION EQUATION: PRESSURE DROP, TEMPERATURE, DEPOSIT THICKNESS

From the blow out experiments, equation representing the removal mass was derived by regression modeling with significant variables including pressure drop across the tube, thickness of deposit layer, and temperature. Regression equation showed the highest coefficient of determination when conducting the general regression with first

order of temperature, thickness and second order of pressure drop. In Equation (1), temperature was in Kelvin, thickness as a unit of μm , and pressure drop of psi.

$$\ln(m_{\text{removal}}) = \alpha(T) + \beta(\delta) + \gamma(\Delta P) + \varepsilon(\Delta P^2) \quad (1)$$

The following is an analysis based on physics in order to evaluate the validity of the regression model.

Pressure Drop

The pressure drop across the tube is a crucial variable in particle removal since it is directly proportionate to the shear force. The relationship between pressure drop and wall shear stress in a horizontal plane tube depends on the length and internal diameter of the tube [22].

$$\tau_w = r \frac{\Delta P}{\Delta L} \quad (2)$$

r corresponds to the effective radius which can be calculated by subtracting deposit thickness from tube inner radius. ΔL is the length of the tube. The scatter plot of Figure 1 is showing the relationship between pressure drop and amount of mass removed at an indicated temperature. It is investigated that there is a different critical pressure drop in particle removal at each temperature. For example, at 50°C, particles start to get removed when the pressure drop is higher than 1.3 psi and at 110°C it starts to abolish after 0.7psi. We can say that once it exceeds the critical pressure drop, mass removal linearly increases as pressure drop gets higher. It seems that in high temperature, layer starts to get removed in a lower pressure drop, which stands for a lower shear stress. Deposit layer property might have changed due to the temperature rise and this phenomenon is also discussed in a later section. It is plausible to assume that removal mass is directly proportional to wall shear stress. Although there is a linear relationship between pressure drop and removal mass after critical ΔP , we used quadratic form in the regression model in order to describe the trend.

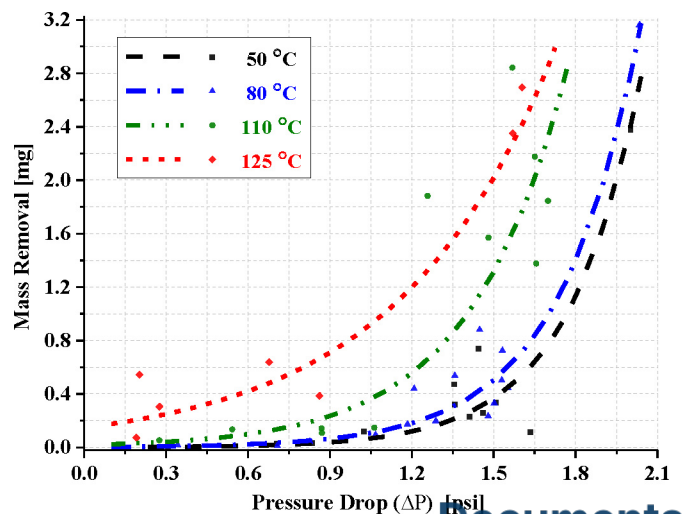


Figure 1. Trend line of removal rate vs. pressure drop in different temperature

Deposit Thickness

Thickness of deposit layer influences the effective diameter. As the layer grows, effective diameter at which the gas flow and the fouling surface meet decreases. It will correspondingly intensify the mean flow velocity. The effective diameter and mean flow velocity are defined as:

$$D = D_I - 2\delta \quad (3)$$

$$U_m = \frac{4\dot{m}}{\rho\pi D^2} \quad (4)$$

D is the effective diameter δ is a deposit thickness. U_m corresponds to exhaust mean velocity. Sluder et al. [19] and Teng et al. [21] claimed that flow velocity is a key parameter influencing the EGR cooler fouling. Also, pressure drop across the cooler is given by [16]:

$$\Delta P = \frac{(f\rho LU_m^2)}{2D} \quad (5)$$

When incorporating Equation (2), (3), (4), and (5),

$$\tau_w = \frac{4f\dot{m}^2}{\rho\pi^2 D^4} = \frac{4f\dot{m}^2}{\rho\pi^2 (D_I - 2\delta)^4} \quad (6)$$

When assuming friction factor is constant at a given mass flow rate, wall shear stress can be expressed as a function of density and effective diameter. It is shown that the development of deposit layer thickness raises the flow induced shear stress. Another potential explanation of relationship between thickness of deposit layer and removal rate is a hydrocarbon fraction along the layer. Although most authors agreed that the soot particles attach to the layer due to the Van der Waals forces, some authors such as Lepperhof [23] argue that HC on the surface act as a “glue”. Han et al. [24] introduces a conceptual model of deposit layer. Fig 2 indicates that high fraction hydrocarbon is formed in the bottom side of the layer. The top part exhibits a dryer condition compared to the bottom. This trend was also observed in Lance et al. [18]

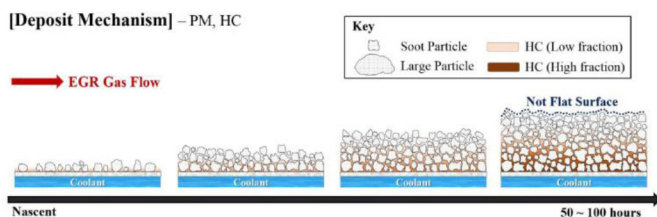


Figure 2. Conceptual model of deposition mechanism with hydrocarbon gradient over the layer [24]

According to their optical microscope image, a dense hydrocarbon layer appeared in a bottom (metal side) layer and a hydrocarbon gradient moving away from the metal. Due to the temperature difference within the deposit layer, the rate of HC accumulation is

unevenly distributed, which can also differentiate the layer properties. As the layer grows, top surface become drier which makes the particles easier to blow out.

The direct relation between deposit layer thickness and removal rate was not well investigated yet, but based on the experiment, there was positive correlation. In this study, it is assumed that removal rate is expressed as first order of thickness.

Temperature

Temperature is another distinct variable that affect particle removal. Salvi et al. [25] suggests that volatile bake-out can significantly change the thermo-physical properties of the deposit layer by conducting the Thermogravimetric analysis (TGA), which is the analytical technique used to determine a material's volatile components by measuring the weight change that occurs as a specimen is heated. Slight decrease in deposit conductivity was detected compared to the pre-bake case, and surface temperature continually decreased while increasing temperature. The principal reason is a higher porosity by volatilized hydrocarbon species as their result shows.

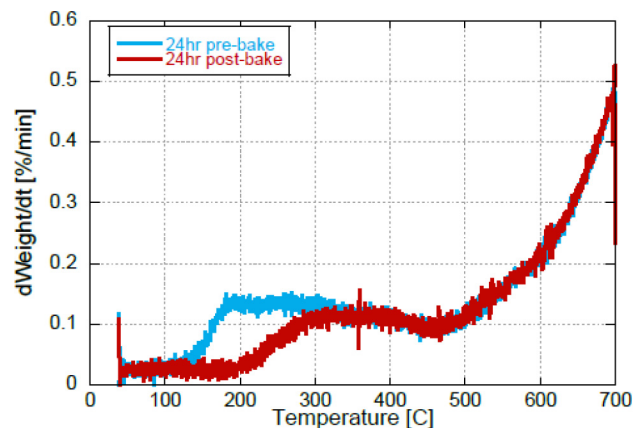


Figure 3. TGA on pre-and post-bake deposit layer [25]

In the experiment described in Part 1, the trend of soot removal distinctively increased above 125°C. Correspondingly, TGA result showed a volatile evaporation accelerates over the similar temperature around 125°C. It is possible that in high temperature, physical properties of deposit layer change due to volatile matter evaporation. Heated layer become porous and dry which makes the surface particles more detachable.

Kinetic energy of particles in soot-deposit interface can also be the factor of removal. We hypothesize that the particle removal can occur when the kinetic energy becomes larger than attaching force, which is known as the Van der Waals force. [9] Kinetic energy in particle can be defined as:

$$K.E. = \frac{1}{2}mv^2 = \frac{3}{2}k_bT \quad (7)$$