

The Effects of Temperature, Shear Stress, and Deposit Thickness on EGR Cooler Fouling Removal Mechanism - Part 1

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

Chih-Kuang Kuan and Daniel Styles
Ford Motor Company

ABSTRACT

Exhaust Gas Recirculation (EGR) coolers are commonly used in diesel and modern gasoline engines to reduce the re-circulated gas temperature. A common problem with the EGR cooler is a reduction of the effectiveness due to the fouling layer primarily caused by thermophoresis, diffusion, and hydrocarbon condensation. Typically, effectiveness decreases rapidly at first, and asymptotically stabilizes over time. There are several hypotheses of this stabilizing phenomenon; one of the possible theories is a deposit removal mechanism. Verifying such a mechanism and finding out the correlation between the removal and stabilization tendency would be a key factor to understand and overcome the problem. Some authors have proposed that the removal is a possible influential factor, while other authors suggest that removal is not a significant factor under realistic conditions. This study identifies the effect of the deposit surface temperature on the removal mechanism with gas velocity and layer thickness variables and concludes that removal does occur under realistic conditions. To investigate the relation, the surface temperature is controlled by setting isothermal conditions of both blowing air and coolant, and the deposit build time is varied to find deposit thickness effects on removal. The blown-out particles are filtered out for mass weighing and size analysis. Additionally, a statistical analysis is conducted and an empirical removal equation is extracted to verify the removal mechanism through modeling. The results show that the removal mechanism has considerable correlation with deposit surface temperature as well as wall shear stress and deposit thickness.

CITATION: Han, T., Sul, H., Hoard, J., Kuan, C. et al., "The Effects of Temperature, Shear Stress, and Deposit Thickness on EGR Cooler Fouling Removal Mechanism - Part 1," *SAE Int. J. Mater. Manf.* 9(2):2016, doi:10.4271/2016-01-0183.

INTRODUCTION

As NO_x (oxides of nitrogen) emission regulations are becoming strict all over the world and customer needs for higher-mileage vehicles increases, the demand of cooled EGR system has augmented in not only diesel but also gasoline vehicles [1,2,3]. Nonetheless, thermal effectiveness drop caused by fouling layer remains one of the biggest problems facing the EGR technology nowadays [4,5,6,7,8,9]. To address the effectiveness problem, a wide range of research studies have been carried out in various approaches such as deposit characteristics study under different fuel and operating conditions, various cooler shape design, material changes and so on [10,11,12,13,14,15]. The ultimate solution, however, is still unreachable due to the absence of a sound fundamental mechanism of effectiveness tendency.

Typically, EGR cooler effectiveness rapidly decreases at first and then asymptotically stabilizes over time. As long as the cooler keeps certain effectiveness, the thermophoretic force caused by temperature gradient continues and the deposit layer grows by the deposit mechanism. But, thermophoresis alone does not explain stabilization unless effectiveness goes to zero, since there will remain a temperature gradient as long as there is cooling. Up to the present, a

couple of hypotheses explaining stabilization have been suggested, and the most plausible theory is a removal mechanism. Stabilization occurs when the removal rate equals to the mass deposition rate.

Several researchers have studied EGR cooler fouling removal mechanism from several points of view including gas flow shear stress, mud cracking, bake out, water condensation and so on [16,17]. Warey et al. and Abarham et al. conducted water vapor condensation washing out experiments, and they discovered that water condensation removal occurs when a dry soot layer exists [18,19,20]. But this rarely happens in real EGR cooler because it arises in a very specific engine condition.

Abd-Elhady et al. conducted a gas flow shear stress experiment about the critical velocity to remove deposit based on soot particle sizes [21]. They argued that at least 40 m/s of gas flow is needed to remove soot from the deposit layer. Sluder et al. studied more realistic experiments about the induced shear flow removal. From their ex-situ removal experiments, they verified the critical velocity to 40~42 m/s under room temperature as well [22]. This velocity at room temperature is, however, at least several times higher than actual EGR cooler gas flow conditions. So they concluded that this will not

happen in real cooler as well. Plus, Paz et al. presented a critical wall shear stress concept and influence of fouling depth by diesel exhaust gas [23].

Salvi et al. ran experiments about bake out test in 120°C and 150°C condition for measuring thermal conductivity [24]. Their observation indicated de-volatilization and compaction of the fouling layer, and a mild shear removal was recognized at low speed condition 10.1 m/s during the bake out. This result raised the possibility of removal under realistic EGR cooler temperature conditions.

The focus of this study is to examine the shear removal with heated surface temperature varying gas velocity and deposit thickness. In addition, based on the experimental result, a regression analysis is conducted to identify the dominant factors and an empirical equation is extracted to verify the removal mechanism through modeling in Part 2.

Shear Stress, Deposit Thickness and Temperature

The three variables discussed here have correlations with each other. Prior to describing the experiments, verifying the relations is important to control the experiments.

The relationship among shear stress, pressure drop and velocity in smooth tube can be described by equation 1 below [25,26]. In the equation, τ_w means wall shear stress, ΔP is pressure drop along the tube and V stands for the gas velocity in the tube.

$$\tau_w = \frac{r_{ac}}{\Delta L} \Delta P \quad \text{and} \quad \Delta P = \frac{f \rho \Delta L}{4r_{ac}} V^2 \quad (1)$$

Therefore, the wall shear stress in the tube is proportional to pressure drop unless the actual radius (r_{ac}) considering both tube diameter and deposit thickness and tube length (ΔL) change. The square of velocity is proportional to pressure drop and shear stress in an equal Reynolds number and temperature condition, since the friction factor (f) and gas density (ρ) are the function of Reynolds number and temperature respectively. So, in the case when temperature, Reynolds number and actual radius are controlled, shear stress, pressure drop, and velocity are regarded to same category of variables.

$$V_{ac} = \frac{1}{\rho_{@temp} \pi r_{ac}^2} \dot{m} \quad (2)$$

Therefore, in this study, the velocities are calculated using equation 2. For calculating the actual velocity, it is assumed that the deposit distribution along the tube is uniform. In addition, the actual radius (r_{ac}) concerning deposit thickness is applied to the actual gas velocity (V_{ac}). The actual radius is calculated by deposit mass, dry soot deposit porosity (0.98) and soot density (1.77 g/cm³) data [27,28]. Additionally, the air density ($\rho_{@temp}$) was matched under each temperature, and the air mass flow rate of removal test rig was measured by mass flow meter. The relations among variables are shown in Figure 1. The blue and green lines (projections onto the 2D planes of δ - ΔP and T - ΔP respectively) indicate that the thickness and

surface temperature have positive correlation to the pressure drop. The red line shows the comprehensive 3D trend between the pressure drop and the others.

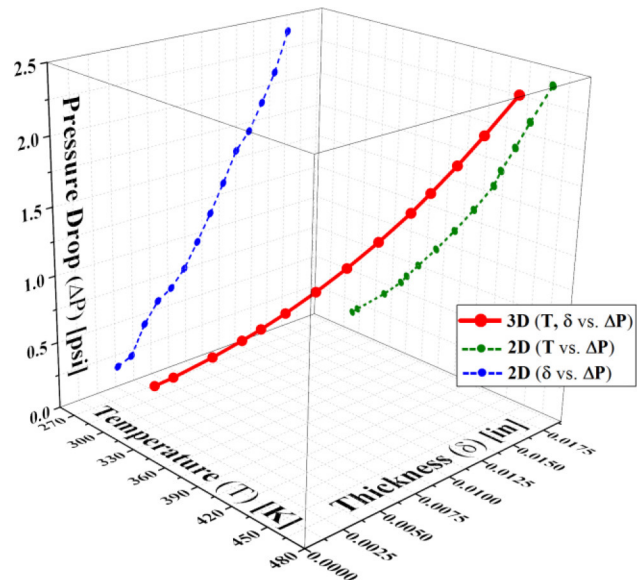


Figure 1. Relation between pressure drop, gas temperature, and deposit mass under experimental conditions.

EXPERIMENTAL SETUP

In order to test the hypothesis that deposit temperature has a relation to shear strength, the overall experiment was divided into two parts; one is deposition and the other is removal test. A 6-tube cooler was used to develop deposits in surrogate cooler tubes; the tubes were then placed in a removal test rig to measure the deposit shear removal. These two test setups are described below.

Deposition Setup

A 2008MY medium duty diesel engine was used for deposition experiments. The University of Michigan in-house shell and tube type external EGR cooler was directly connected to the engine exhaust pipe, taking a flow sample ahead of the engine's own EGR cooler, so that the EGR cooler condition was same as the high pressure EGR coolers. Also, the flow rate was measured and controlled by an orifice meter and valve after cooler. The target EGR inlet gas temperature was 280°C, and coolant was controlled to 70°C for all deposition experiments. The deposit condition from exhaust gas was a dry soot condition; average 11.5ppm of total hydrocarbon (C₃ based) and 1.5 FSN (Filter Smoke Number). For maintaining these exhaust conditions, the engine was controlled at 1200 rpm, 7.5 bar of brake mean effective pressure and 2.0 mg/stroke at 30 aTDC of additional post injection ECU control. Plus, to maintain the combustion condition constantly, the intake air temperature and humidity condition was controlled to 70°F (21.1°C) and 50% of relative humidity.

The in-house EGR cooler design is illustrated in figure 2 [10]. The removable 6 surrogate stainless steel seamless tubes were installed into the cooler housing with graphite ferrules on both sides to avoid tube damage. The tube outer diameter is 0.25 in (6.35 mm) and wall

thickness is 0.02 in (0.508 mm), and the total and coolant affected tube length is 13.375 in (339.725 mm) and 10.7 in (271.78 mm) respectively. The coolant direction is counter flow, and the temperature was controlled by NESLAB RTE-100 closed loop recirculating chiller.

The total flow rate of the 6 surrogate tubes was controlled to 180 SLPM, so each tube had 30 SLPM exhaust gas flow condition. The fouled tubes were put in the constant humidity (RH 50%) chamber for 48 hours after deposition to standardize the light hydrocarbon and humidity condition. Also, the total deposit mass gain was measured by Sartorius A200S balance (accuracy 0.1 mg).

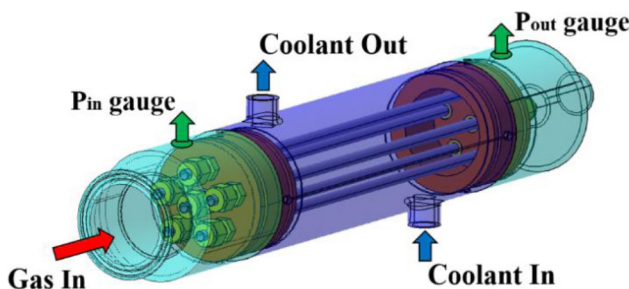


Figure 2. UM In-house shell and tube type EGR cooler deposition rig.

Removal Test Setup

The removal test rig clarified in figure 3 was designed to control the deposit surface temperature using external high temperature coolant. The tube was placed in the test fixture, and the coolant and air flow were preheated with no flowing condition. Both flows were started to bring the tube to an isothermal temperature as rapidly as possible. To heat the surface temperature up to the target, all tubes were heated up within 120 seconds using heated coolant. This duration of pre-heat was decided based on the measured time of coolant stabilization and the heat flux calculation. Thus, the tube is held at a constant temperature, with air flow through it.

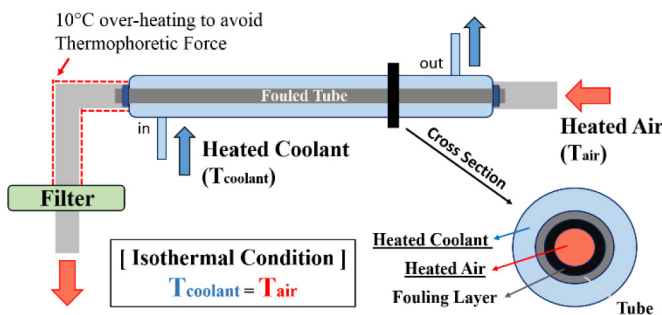


Figure 3. Removal test apparatus for isothermal control.

All of the removed particles are captured by Pall Life Science EMFAB 90mm filter right after removal apparatus. The capture efficiency of the filter is 99.9% of dioctyl phthalate aerosol retention rating at 32 liter/min air speed based on ASTM. Also, the wall temperature of stainless steel line between the tube and filter was controlled to 10°C higher than the test temperature to avoid particle sticking caused by thermophoretic force. After the removal test, filters are put in the constant humidity chamber (RH 50%) for 1 hour and weighed by Sartorius MSP balance (accuracy 0.001 mg).

Testing Procedure

To verify the effects of surface temperature, shear stress, and fouling thickness, the test matrix was built as shown in table 1. The basic set of all removal tests was 6-hour deposition, and the surface temperatures for blow out were varied from ambient temperature to 165°C. As described in introduction part, the actual velocity was converted from nominal velocity at STP with temperature condition, and it was measured and calculated by MKS mass flow meter. The baseline velocities were 20 m/s (actual EGR cooler condition), 40 m/s (critical velocity in ambient temperature), and 60 m/s (higher velocity case). The total blowing out test was conducted during 10 minutes.

Table 1. Test Matrix for each surrogate tube.

Set	Deposit Time [hour]	Air Velocity [m/s]	Surface Temperature [°C]
# 1	6	20, 40, 60	25, 50, 65, 80, 95, 110, 125, 140, 165
# 2	6	45, 50, 55, 65, 70	50, 80, 110
# 3	3	20	50, 80, 110, 125, 145, 165
# 4	6, 12, 18, 24	20, 60	50, 80, 110, 125, 145, 165

RESULTS

Deposition: Effectiveness and Deposit Mass

The first step of all experiments was 6-hour deposition (except one set of 3-hour case). Longer duration depositions were completed by running 6 hour increments (one day's testing). After each 6 hour deposition, tubes were removed, equilibrated 48 hours in constant humidity chamber, weighed, and reinstalled. Most of the effectiveness results started from 64~65 percent after the coolant temperature and exhaust flow rate stabilization, and it decreased around 7.5 percent during initial 6 hours deposit. In the multiple hour cases, the rate of effectiveness loss decreased as the deposit continued, and the average of effectiveness after 24 hours was around 47 percent. Figure 4 shows a 24-hour multiple deposit effectiveness trends used in Part 2 modeling with blue color, and 10 grey color trends with same condition experiments. On the basis of effectiveness data from the literatures [7,30], the typical stabilization time is from 50 to 100 hours, and a common thermal effectiveness drop rate is 30 percentage of starting value. Therefore, the expected thermal effectiveness value is 0.45 in 50~100 hours, and the experimental trend is sound. Also, figure 5 illustrates the pressure drop trend of multiple hour deposition.

Figure 6 shows the deposit mass results of the total specimens, and it was classified by the deposit durations. The subdivisions of the bars reflect the individual 6 hour runs; thus, for sections in the 24 hour bar. As the duration of deposition increases, the incremental rate of the deposit mass was gradually decreased in accordance with the effectiveness tendency. Also, because of the shell and tube type geometry shown in figure 2, the center located tube had maximum 4 percent more deposit than the other five surrounding tubes. Plus, there were slight total mass differences between summer and winter experiments. Consequently, these uncertainties are applied to the error bar on the mass gain graph.