

Review of Soot Deposition and Removal Mechanisms in EGR Coolers

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ABSTRACT

Exhaust gas recirculation (EGR) coolers are commonly used in diesel engines to reduce the temperature of recirculated exhaust gases in order to reduce NOX emissions. Engine coolant is used to cool EGR coolers. The presence of a cold surface in the cooler causes fouling due to particulate soot deposition, condensation of hydrocarbon, water and acid. Fouling experience results in cooler effectiveness loss and pressure drop. In this study, possible soot deposition mechanisms are discussed and their orders of magnitude are compared. Also, probable removal mechanisms of soot particles are studied by calculating the forces acting on a single particle attached to the wall or deposited layer. Our analysis shows that thermophoresis is the dominant mechanism for soot deposition in EGR coolers and high surface temperature and high kinetic energy of soot particles at the gas-deposit interface can be the critical factor in particles removal. High surface temperature causes thermal forces between particles and overcomes Van der Waals and results in particles removal. This study led us towards a hypothesis for possible removal mechanisms of soot particles from the deposited layer.

INTRODUCTION

Exhaust gas recirculation (EGR) has proven to be an effective way of reducing nitrogen oxides (NOX) formation during the combustion process in compression-ignition engines for both conventional and low-temperature combustion modes. By returning a portion of exhaust gas to the engine, the flame temperature decreases, and engine out NOx can be drastically lowered by reduced peak in-cylinder temperature.

Most current diesel engines have a single EGR cooler, using engine coolant (supplied at 80-90°C) to cool the EGR. EGR coolers have been used for several years in both North American and European markets at low EGR rates, and typically with cooler-out EGR temperatures above 120°C. However, future emission standards (2010) will require increased EGR flow rates and reduced temperatures. EGR rate in diesel engines needs to be increased in the future. This is likely to lead to deposition of soot, hydrocarbons, and acids in the EGR cooler.

The buildup of deposits in EGR coolers causes significant degradation in heat transfer performance, often on the order of 20-30%. Deposits also increase pressure drop across coolers. It is unlikely that EGR cooler deposits can be prevented from forming when soot and hydrocarbon are present. The presence of cooled surfaces will cause soot deposition and condensation of HC and acids. It is generally felt that dry fluffy soot is less likely to cause major fouling than heavy wet soot. Experimental data indicate that majority of deposited mass is due to particulates and only a small fraction of hydrocarbons condense on tubes [1]. In this article, a summary of possible soot particles deposition and removal mechanisms is given and the most dominant ones are determined.

DEPOSITION MECHANISMS

Before describing deposition mechanisms, the soot particulate distribution in EGR flows must be determined. Harris and Maricq [2] studied the EGR particle distribution in many different conditions. A normalized semi-logarithmic distribution is offered in the aforementioned work as:

$$m = \frac{1}{\sqrt{2\pi} \ln(\sigma_g)} \exp \left[-\frac{\ln(h)^2}{2 \ln^2(\sigma_g)} \right] \quad (1)$$

where:

$$\log h = \log(d_p) - \langle \log(\mu_g) \rangle \quad (2)$$

It is also shown that the mean particle size is $\mu_g = 57.3 \text{ nm}$ and the standard deviation is $\sigma_g = 1.8$. Figure 1 illustrates the normalized particle distribution in EGR flows [2].

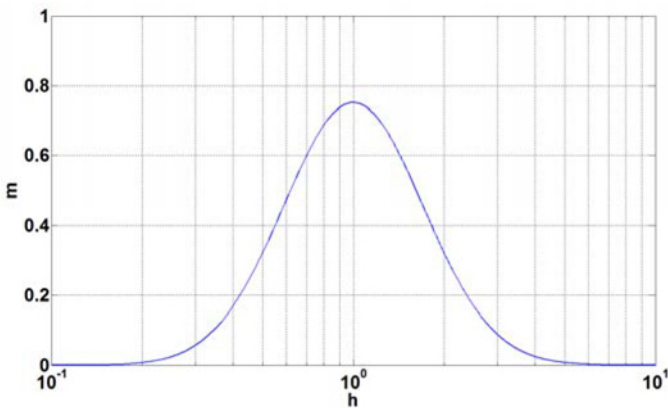


Figure 1. normalized semi-logarithmic EGR soot particles distribution

One can show the accumulative soot particles distribution as:

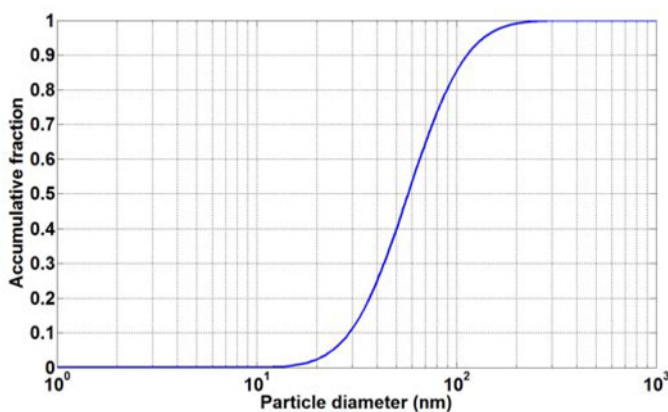


Figure 2. Accumulative EGR soot particles distribution

It is noted that the EGR soot particle range is between 10nm to 300nm. It can be seen from Figure 2 that almost 50% of

soot particles have a size of 60 nm and less. This number will be used later to show how the deposition mechanism for small particles on this range differ from the deposition of larger particles. The fractional distribution of soot particles can also be shown as:

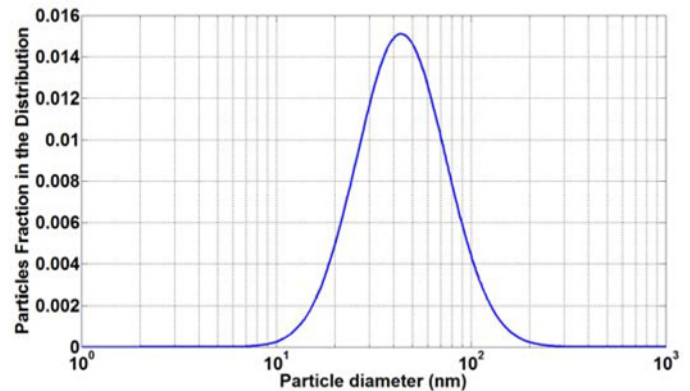


Figure 3. EGR soot particles fractional distribution

Deposition mechanisms in general are thermophoresis, eddy diffusion, turbulent impaction, electrostatic, and gravitational. In subsequent sections, these mechanisms will be discussed but a fixed reference is required for a quantitative comparison of different mechanisms.

To compare the numbers quantitatively, rational numbers are selected from our modeling works ([3] and [4]) for a tube geometry and its boundary conditions (listed in Table 1).

These numbers help us compare the mechanisms in next sections. Figure 1 shows a schematic of a tube in EGR cooler. The tube length (L), tube diameter (D), inlet and mean temperature (T_{inlet} , T_m) and concentration of particles (C_{inlet} , C_m) are demonstrated.

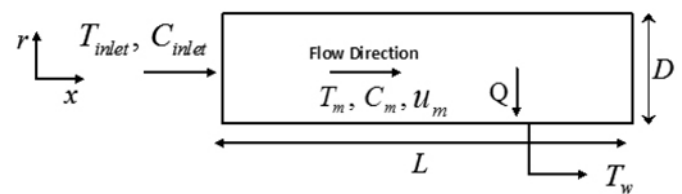


Figure 4. Schematic of a surrogate tube and EGR flow

Table 1. Geometry and boundary condition of a surrogate tube

Tube Inside Diameter	5.5 mm
Tube Length	0.3 m
Averaged Temperature	600 K
Wall Temperature	363 K
Averaged velocity	25 m/s
Averaged pressure	200 Kpa
Averaged gas viscosity	0.0000317 Kg/ms
Averaged gas density	1.17Kg/m3
Averaged concentration	30 mg/m3
Particle density	1770 kg/m3
Averaged sublayer thickness	100 μm
Averaged Shear velocity	1.7 m/s

Deposition flux of particles is defined as summation of all deposition velocities times by particle concentration as:

$$J = C_m (V_{th} + V_t + V_d + V_e + V_i + V_g) \quad (3)$$

Having same numbers for comparison, one is able to compare the deposition velocities for different mechanisms that are listed below:

THERMOPHORESIS

Thermophoresis is a particle motion generated by thermal gradients. Thermophoresis is the phenomenon that when a temperature gradient exists, particles move toward the cooler direction (Figure 5). This force arises from the fact that hotter gas molecules have higher velocity. Thus, in a thermal gradient the gas on the hot side of the particle hits with higher force than the gas from the cooler side, and a net force is created toward the cooler region. As particles are transported from the bulk gas flow into the boundary layer near the surface, they enter a region of large thermal gradient and thus are thermophoretically driven toward the wall. Particles reaching the wall stick to the wall due to Van der Waals forces [5].

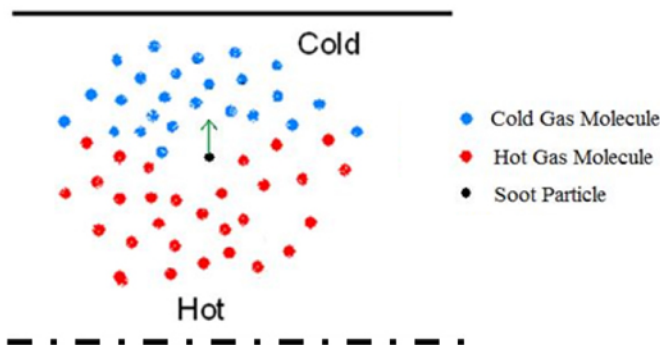


Figure 5. Schematics of thermophoresis phenomenon

Researchers have studied thermophoresis and there are many correlations in literature for the thermophoretic force and velocity. Two common correlations are Brock-Talbot and modified Cha-McCoy-Wood (MCMW) correlations that are explained below:

BROCK-TALBOT CORRELATION

The thermophoretic drift velocity of a particle in a pipe flow (radial gradient) is defined as:

$$V_{th} = -K_{th} \frac{v}{T} \vec{\nabla} T = -K_{th} \frac{v}{T} \frac{\partial T}{\partial r} \quad (4)$$

$$K_{th} = \frac{2C_s C_c}{(1 + 3C_m Kn)} \times \frac{k_g/k_p + C_t Kn}{1 + 2k_g/k_p + 2C_t Kn} \quad (5)$$

where:

$$\text{Cunningham correction factor: } C_c = 1 + Kn(A + Be^{-C/Kn}) \quad (6)$$

A, B, C, C_s, C_m, C_t : Thermophoretic constants which are 1.257, 0.4, 1.1, 1.14, 1.17, and 2.18 respectively.

MCMW CORRELATION

Thermophoretic force in the MCMW equation is defined as:

$$F_{th} = 1.15 \frac{Kn}{4\sqrt{2}\alpha(1 + \frac{\pi_1}{2}Kn)} \cdot [1 - \exp(-\frac{\alpha}{Kn})] \cdot (\frac{4}{3\pi} \phi \pi_1 Kn)^{1/2} \frac{k_b}{d_m^2} \nabla T d_p^2 \quad (7)$$

where:

$$\pi_1 = 0.18 \frac{\frac{36}{\pi}}{(2 - S_n + S_t) \frac{4}{\pi} + S_n}, \alpha = 0.22 \left[\frac{\frac{\pi}{6} \phi}{1 + \frac{\pi_1}{2} Kn} \right]^{1/2} \quad (8)$$

Thermophoretic drift velocity can also be calculated as:

$$V_{th} = \frac{F_{th} \tau}{m_p} = \frac{F_{th} \tau}{\rho_p \pi d_p^3 / 6} \quad (9)$$

where τ is the particle relaxation time defined by:

$$\tau = \left(\frac{\rho_p d_p^2 C_c}{18\mu} \right) \quad (10)$$

It is usual to choose Brock-Talbot equations in articles; however, there is a criterion for employing that equation. He and Ahmadi [6] studied the thermophoretic deposition of particles and compared Brock-Talbot equation with the MCMW correlation. By comparing experimental measurements in their work (not presented here), it became obvious that Brock-Talbot equation deviates from experimental results [7,8] when particles are very small and the Knudsen number is less than 2. Considering the Knudsen number and the gas molecules mean free path equations,

$$Kn = \frac{2\lambda}{d_p}, \quad \lambda = \frac{2\mu}{\rho} \left(\frac{\pi MW}{8R_u T} \right)^{0.5} \quad (11)$$

one is able to figure out when the particle diameter equals to the mean free path of gas molecules, the Knudsen number is 2. So, if the particle diameter is less than the mean free path of gas molecules, the gas medium is not considered continuous anymore. It is recommended by He and Ahmadi [6] to use Brock-Talbot equation when $Kn < 2$ and the MCMW equation when $Kn > 2$.

By assuming a 200Kpa mean pressure inside the tube and a mean temperature of 600K (Table 1), one can calculate the mean free path of EGR gas molecules to be 78 nm. Therefore, the Knudsen number range for EGR flows varies between 0.16 (for $d_p=1000$ nm) and 15.6 (for $d_p=10$ nm). Figure 6 compares above correlations for a wide range of Knudsen numbers in EGR flows.

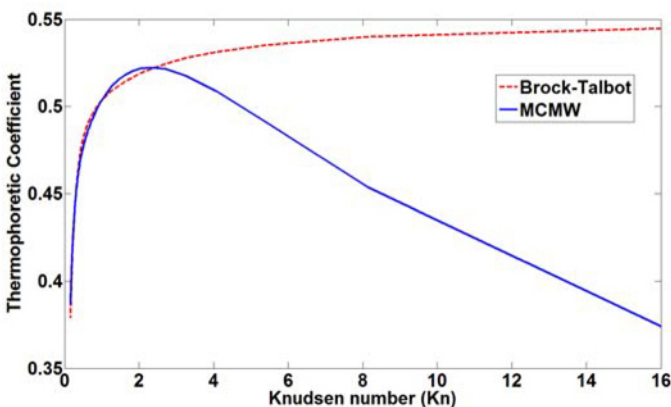


Figure 6. MCMW and Brock-Talbot correlations comparison

Since more than 50% of particles have a diameter less than 60 nm (Figure 2), it is more highlighted that using Brock-

Talbot equation over-predicts the thermophoretic deposition by a few percent. So, instead of taking the mean particle diameter, a weighted thermophoretic coefficient can be calculated for the whole range of particles diameter. The fraction of each particle is calculated based on the accumulative distribution. Also, the thermophoretic coefficient of each particle can be calculated from the Brock-Talbot formula (for $Kn < 2$) and the MCMW (for $Kn > 2$). Then, an equivalent thermophoretic coefficient is:

$$K_{th} = \sum_{i=1}^{1000} K_{th,i} \cdot Fraction_i \quad (12)$$

For the presented case in Figure 2, an equivalent thermophoretic coefficient is 0.5104; however, Brock-Talbot equation predicts it to be 0.5278 (3.4% error) and the MCMW predicts it to be 0.5214 (2.2% error).

Finally, considering the above correlation for the thermophoretic coefficient, one can find an equivalent thermophoretic deposition velocity of particles as 0.025 m/s for a temperature gradient of [6].

$$\nabla T = \frac{u^{*2} (T_m - T_w)}{\nu(u_m - u^*)} = 1.1 \times 10^6 \text{ K/m} \quad (13)$$

Figure 7 demonstrates thermophoretic velocity of submicron particles at the given boundary condition.

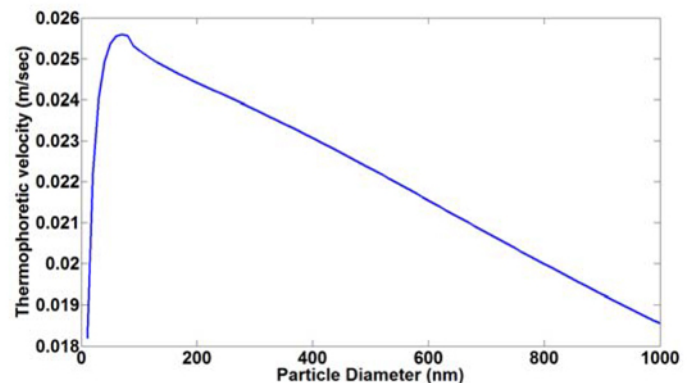


Figure 7. Thermophoretic velocity for submicron particles at the given boundary condition

EDDY DIFFUSION

Submicron particles could be easily moved by the eddy motion toward the wall. The migration of particles from a higher concentration region to a lower one is called diffusion. Diffusion can be well described by the well-known Fick's

law. The deposition velocity due to diffusion in a turbulent flow is [9]:

$$V_d = 0.057u^* Sc_p^{-2/3} \quad (14)$$

Where Schmidt number of particles is defined as the ratio of gas kinematic viscosity to the particles diffusion coefficient:

$$Sc_p = \frac{\nu}{D_p} \quad (15)$$

The particles diffusion coefficient is also defined by:

$$D_p = \frac{k_b T_m C_c}{3\pi\mu d_p} \quad (16)$$

The diffusion mechanism is more effective for smaller particles (10-50 nm) in the submicron range due to their lower Schmidt numbers. The diffusion velocity for the smallest soot particle (the largest diffusion velocity) is calculated to be $1.9 \times 10^{-3} \text{ m/s}$ (Figure 8). Diffusion velocity for small particles (less than 50nm) is one order of magnitude less than the thermophoretic velocity but it is not comparable with the thermophoretic velocity for larger particles at all. Overall, diffusion is not also an effective mechanism for EGR soot particles deposition even for small particles.

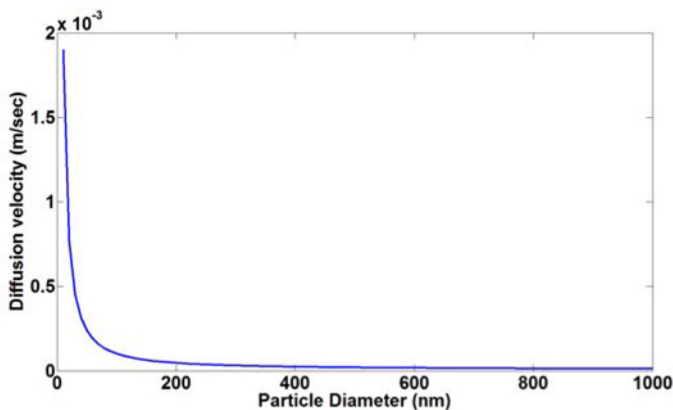


Figure 8. Diffusion velocity for submicron particles at the given boundary condition

TURBULENT IMPACTION

For many heat exchangers operating in dusty flows, particles can be inertially deposited. This occurs when the particle is large enough that it cannot easily follow rapid changes in the

gas flow direction. However, small particles have very short relaxation times and thus follow the flow. A measure for the inertia of a particle is the particle relaxation time τ . The particle relaxation time should be compared to the smallest time scale of the flow that is the Kolmogorov scale k_K and the largest time scale of the flow k_L . When the particle relaxation time is larger than the largest time scale, the particle transport is controlled inertially but when it is between the two aforementioned scales, the transport is under the control of eddies. The two scales are defined by:

$$k_K = \sqrt{\frac{\nu L}{U^3}} \quad (17)$$

$$k_L = \frac{L}{U} \quad (18)$$

Where L is taken as the tube radius and U is the core flow velocity. For the condition that the model ran, the core flow velocity is about 25 m/sec and the tube inner diameter is 5.5 mm. So, the Kolmogorov time scale is $\sim 2 \times 10^{-6}$ and the largest time scale is $\sim 1 \times 10^{-4}$. Substituting above numbers, one can find out that the inertial is important for particles of $\sim 5 \mu\text{m}$ and larger while transport starts to be controlled by eddies for submicron particles. Above calculations and Figure 1 show that the particle transport in EGR flow is not inertially controlled. Another way of comparison is to find the drift velocity due to the inertial impaction for a turbulent flow as [9]:

$$V_i = 4.5 \times 10^{-4} u^* (\tau / (\nu / u^{*2}))^2 \quad (19)$$

Since there is a wide distribution of particle diameters, the largest deposition velocity (corresponding to $dp=1000 \text{ nm}$) is calculated to be 1.6×10^{-4} that is not comparable with the thermophoretic velocity.