

## FOULING PROBLEMS IN EXHAUST GAS RECIRCULATION COOLERS IN THE AUTOMOTIVE INDUSTRY

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### ABSTRACT

Transportation is responsible for approximately 20% of global greenhouse gas emissions, such as CO<sub>2</sub>, NO<sub>x</sub> and hydrocarbons which have not been burned completely in the engine. In particular, 55% of globally emitted NO<sub>x</sub>, which is more harmful to the environment than CO<sub>2</sub>, is produced by the automotive industry alone. Strict emission standards are now in place that set specific limits to the amount of pollutants that can be released into the environment. The widely used measure to reduce NO<sub>x</sub> emissions in diesel engines is to return part of the exhaust gas to the intake of the engine. This is usually done through via a heat exchanger known as exhaust gas recirculation (EGR) cooler. However, EGR coolers are subject to severe fouling such that their thermal efficiency can drop by as much as 30% within a very short period of time. More importantly, the deposit layer is a blend of particulate matter and sticky heavy hydrocarbons that are very difficult to remove from the heat exchanger surfaces. The present study addresses this problem and provides a review on required R&D activities to mitigate fouling of EGR coolers.

### INTRODUCTION

Diesel engine emissions, especially nitrogen oxides (NO<sub>x</sub>), CO<sub>2</sub> and particulate matter (PM), impose a major threat to the environment, in terms of global warming and carcinogenic particles. Accordingly, strict emission legislation has been imposed worldwide that limits the amount of pollutants that can be released into the environment. Table 1 lists some of these emission rules for heavy-duty diesel engines in Europe. Compared to the current level, 75% reduction in NO<sub>x</sub> emissions is required by the year 2013.

Table 1 European emission standards for heavy-duty diesel engines, g/kWh

| Year | Reference | CO  | HC   | NO <sub>x</sub> | PM   |
|------|-----------|-----|------|-----------------|------|
| 2005 | EURO IV   | 1.5 | 0.46 | 3.5             | 0.02 |
| 2008 | EURO V    | 1.5 | 0.46 | 2.0             | 0.02 |
| 2013 | EURO VI   | 1.5 | 0.13 | 0.4             | 0.01 |

Exhaust gas recirculation (EGR) is a nitrogen oxide emission reduction technique used in most gasoline and diesel engines. EGR works by recirculating a portion of the engine's exhaust gas back to the cylinders. Mixing the incoming air with recirculated exhaust gas dilutes the inert

gas concentration, and hence lowers the flame temperature. Because NO<sub>x</sub> formation progresses much faster at high temperatures, EGR serves to limit the generation of NO<sub>x</sub>. Jacobs et al. (2003) measured the influence of EGR on NO<sub>x</sub> emissions for three different loading conditions: 1200 rpm – 50 % load, 1200 rpm – 20 % load and 1800 rpm – 50 % load, and the results are presented in Fig. 1. It can be seen that for all three operating conditions NO<sub>x</sub> concentration decreases with increasing EGR rate.

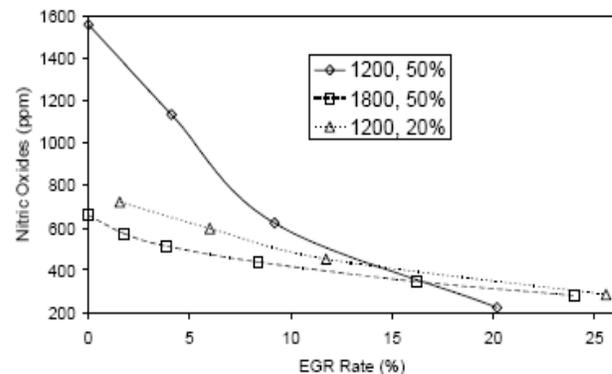


Fig. 1 Nitric Oxide emissions versus EGR Rate (Jacobs et al., 2003).

McKinley (1997) has demonstrated how a cooled exhaust gas recirculation system can reduce emissions, and Lim et al. (2004) have studied the controlling attribution of EGR temperature and exhaust properties with the change of operation conditions. Both studies show that NO<sub>x</sub> is significantly reduced by using the EGR cooler, while more PM is produced due as a trade-off. Three mechanisms (Ladommatos et al., 1996a; 1996b and 1997) have been determined through which EGR operation affects combustion, and hence NO<sub>x</sub> formation and reduction:

- 1- *Dilution Mechanism:* The potentially increased mixing time and longer burn duration caused by the EGR's dilution effect result in lowered flame temperatures. In addition, the EGR decreases the partial pressure of oxygen thus due to lower temperature and availability of less oxygen then less nitrogen oxides are expected to be produced.
- 2- *Thermal Mechanism:* The increased heat capacity of an EGR-laced mixture results in lowered flame temperatures.

- 3- *Chemical Mechanism:* Increased dissociation of the more complex EGR molecules (such as  $\text{CO}_2$  and  $\text{H}_2\text{O}$ ) results in lowered flame temperatures.

Exhaust gas from engines are cooled in order to lower emissions via an EGR cooler. Kowada et al. (2006) tested a diesel engine with a basic EGR cooler and found that with better charge cooling, the engine produces significantly less  $\text{NO}_x$  with no loss in BSFC. Kowada et al. (2006) used a production catalyzed wall-flow DPF to reduce PM emissions in both mass and small particles. For these reasons, EGR coolers are very desirable in diesel engines when lower emissions are required.

## 1. FUNDAMENTALS OF EGR

There are two ways to introduce exhaust gases inside the combustion chamber of an engine. One possibility is to change the timing of the valves, which is called internal EGR. The exhaust valve can be closed before all of the burned gas has left the engine cylinder. Alternatively, the exhaust valve can be kept open at the beginning of the intake cycle such that the difference in pressure between the combustion chamber and the exhaust pipe results in sucking back the exhaust gasses. This technique is limited in its operation and cannot achieve the set emission regulations. The second way is to return back a fraction of the exhaust gas to the inlet manifold, which is known as external EGR. This allows higher ratios of EGR, and strongly reduces  $\text{NO}_x$  and particulate emissions. EGR cannot be used over the whole range of operating loads and it has to be carefully controlled. The amount of EGR is strongly depended on the operating load, such that excessive EGR can lead to ignition delay and a higher probability of misfire.

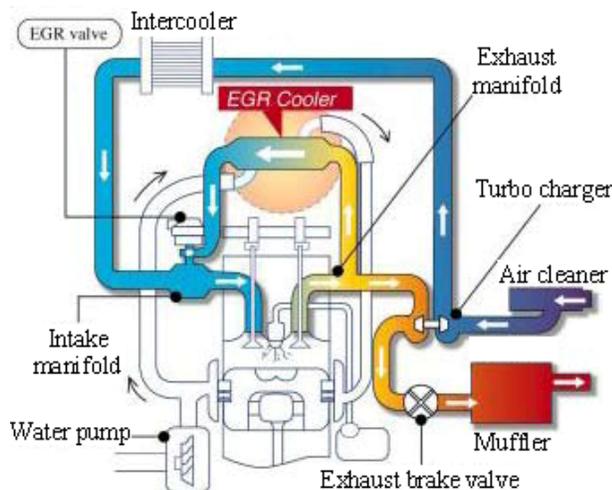


Fig. 2. EGR cooling system. Adopted from Tokyo Radiator Mfg. Co. Ltd (2009).

### Principle of Operation of EGR Coolers

By recirculating exhaust gas back into the engine cylinders, EGR lowers the flame temperature and thereby reduces  $\text{NO}_x$ . EGR coolers further lower the temperature of the exhaust gas before recirculation by cooling it with the

water coming from the radiator of the engine, thereby achieving an even greater reduction in  $\text{NO}_x$ . A schematic of the EGR cooling system is shown in Fig. 2. However, the constant use of cooled exhaust gas results in the engine taking longer to reach optimal combustion temperatures. Incomplete combustion and associated emissions can result during that period. Tokyo Radiator's new EGR cooler has a built-in bypass channel to send exhaust gases directly back to the combustion chambers when the engine temperature is low. Sensors calculate the engine temperature from the temperature of the radiator coolant, and a pressure valve opens the bypass channel whenever the temperature is below a set value. This helps the engine to warm faster and reduces the time for incomplete combustion.

### Types of EGR Coolers

The EGR cooler can be a simple heat exchanger, in which the temperature of exhaust gases is reduced by the coolant from the cooling system of the engine. The EGR cooler comes in different forms; however, none is capable of preventing fouling. The most common type is the shell and tube cooler, as shown in Fig. 3. A cross-section of the cooler is shown in Fig. 3b). The exhaust gases pass through the tubes and are cooled by the coolant flowing on the shell-side. Kim et al. (2008a) investigated the effectiveness of shell & tube and stack type EGR coolers. An image of the investigated stack-type cooler is shown in Fig. 4, which is a plate-fin heat exchanger. Kim et al. (2008a) found that the stack-type cooler has 25-50 % higher effectiveness than the shell & tube type, mainly due to an increased surface area and a better mixing of the exhaust gas flow. Kim et al. (2008b) also examined the fouling behaviour of a shell & tube EGR cooler with plain tubes and spiral tubes. The fouling tests showed severe clogging in the tubes after only 62 hrs of operation, as can be seen in Fig. 4.c.

### EGR Systems

There are two possible ways by which an EGR cooler can be connected, known as the high pressure and the low pressure EGR loops. In a high pressure loop, EGR gas is taken from the exhaust upstream of the turbocharger turbine, cooled through the EGR cooler and then mixed with compressed intake air at the turbocharger compressor outlet. Thus the EGR system operates substantially at boost pressure. In a low-pressure loop, EGR gas is taken from the exhaust downstream of the turbocharger turbine, and mixed with the intake air generally between the air filter and the turbocharger compressor inlet. Thus, the system essentially operates at atmospheric pressure. A low-pressure loop EGR system can take EGR gas from downstream of the after treatments system, including the diesel particulate filter (DPF). As a result, the recirculated exhaust can be free of particulates and unburned hydrocarbons (HC), and thus the cooler can be kept much cleaner. However, it appears that the majority of manufacturers plan to use high-pressure loop EGR because it may offer somewhat better fuel efficiency (Leet et al., 1998; Lundqvist et al., 2000; Van Aken et al., 2007).

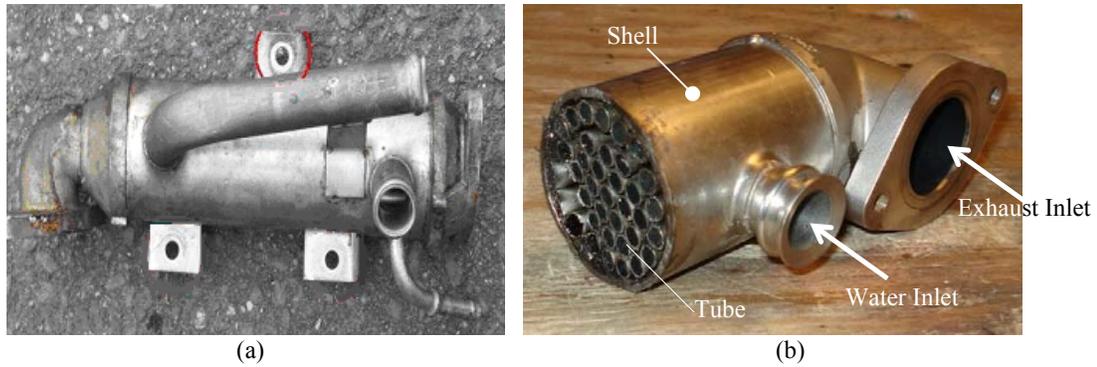


Fig. 3. Shell and tube EGR cooler (a) and a cross-section through the cooler (b). The inner tubes are plain round tubes.

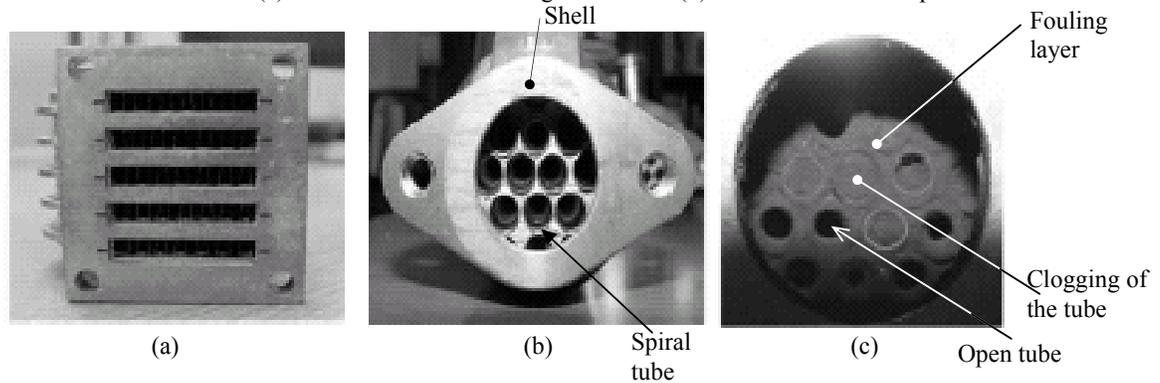


Fig. 4. Stack type EGR cooler (a) and shell and spiral tube (b) cooler. Fouling of the shell and spiral tube cooler (c) after 62 hrs of operation. Adopted from Kim et al. (2008a) and Kim et al. (2008b).

## 2. FOULING OF EGR COOLERS

Ash deposits in EGR coolers form an insulating layer that adds thermal resistance between the coolant and the hot exhaust gases. The fouling layers decrease the thermal efficiency and increase the pressure drop in the EGR cooler, which degrades the efficiency of the engine and leads to higher  $\text{NO}_x$  emissions. Bravo et al. (2005) measured the loss in EGR cooler effectiveness as a function of the mileage in a test vehicle. The results are presented in Fig. 5. It can be seen that as the deposits build up, the coolers become less effective. Fouling of EGR coolers tends to be one of the predominate factors of EGR systems failure.

Zhan et al. (2008) measured particulate fouling in an EGR cooler connected to a 7.3 Liter V8 diesel engine, and found that if the exhaust gases are fed directly into the cooler without any treatment the pressure drop in the EGR cooler increased by 61 % from its initial state within 42 hrs of operation. The change in the temperature drop across the gas cooler due to fouling is  $-6^\circ\text{C}/\text{hr}$ , the negative sign indicating that the exit gases from the cooler become hotter every hour by six degrees. Zhan et al. (2008) report that after 42 hrs of operation the system stabilizes, such that the pressure drop across the gas cooler becomes constant and also the exit temperature remains constant. This indicates that fouling at the beginning of operation is very fast, but stabilizes afterwards, which is known as asymptotic behaviour and observed mainly in conjunction with particulate fouling (Abd-Elhady et al., 2005a). Zhang et al. (2004) investigated the influence of particulate matter in the exhaust gases of a diesel engine on the performance of an

EGR cooler. The effectiveness of the tested gas cooler, the thermal resistance and the mass flow rate of the exhaust gasses as a function of time are shown in Fig. 6. It was found that the fouling caused by the diesel exhaust had a significant impact on the performance of the EGR-cooler during 12 hours of operation. The thermal resistance of the cooler increased continually throughout the test period, but the rate of increase of the thermal resistance decreases with time until it reaches an asymptotic value, which is similar in behaviour to the results presented by Garrett-Price et al. (1985). The thermal resistance increased by 100% in approximately 3 hrs and by 150% in 12 hrs. The effectiveness of the heat exchanger decreased from approximately 0.7 to 0.4 during the 12 hour test indicating that fouling had a significant effect on the performance of the EGR cooler.

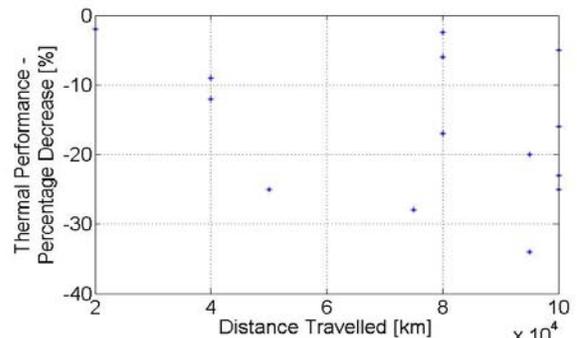


Fig. 5. Loss of EGR cooler effectiveness versus mileage in vehicle testing (Bravo et al., 2005).

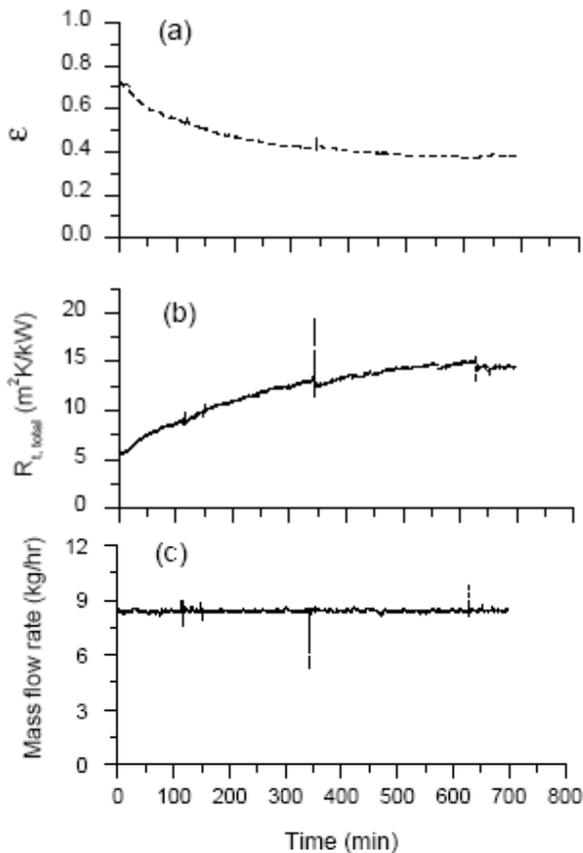


Fig. 6. Change in the gas cooler (a) effectiveness and (b) thermal resistance with time. The mass flow rate of the exhaust gasses across the gas cooler is shown in (c). Adopted from Zhang et al. (2004).

There are four conditions that promote fouling of an EGR cooler (Anthony, 2007): i- high concentration of particulate matter at the inlet of the cooler, ii- high gas temperature gradient across the cooler, iii- low gas outlet temperature that promotes condensation inside the cooler and iv- wet particles in the exhaust gasses. Therefore, it must be expected that the performance of the EGR cooler shown in Fig. 6 is a function of the operating condition of the diesel engine. Diesel engines that run intermittently face considerably more severe fouling conditions because of condensation of volatile particles which occurs at the beginning of start-up. Here, the tube surfaces of EGR coolers are so cold that condensation of a large amount of hydrocarbons and particles becomes possible.

### Fouling Mechanisms

Soot formation in engines is a very complex issue, and understanding fouling involves knowledge of fuel characteristics, soot behaviour and operating conditions. Soot formation, transport and deposition mechanisms have been proposed (Baxter, 1988; Benson et al., 1993; Visser, 1988). The produced exhaust gas contains mainly  $CO$ ,  $CO_2$ ,  $H_2O$ ,  $H_2$ ,  $CH_4$ , un-burnt hydrocarbons, fine soot particles

and nitrogenous compounds which once passed through the EGR cooler would form a very hard fouling layer which is mainly a mixture of soot and hydrocarbons. The presence of different precursors on the surface underlines the fact that perhaps various fouling mechanisms such as particulate, sedimentation due to spinning and gravity and solidification each would play a role. However no attempt is made so far to discern the contribution of each fouling mechanism individually to the ultimate fouling of EGR coolers.

The contaminants deposit on the tubes of the EGR cooler forming an insulating layer, which reduces the overall heat transfer coefficient and can result in operational failure. Particulate fouling is defined as the accumulation of particles on a heat transfer surface forming an insulating powdery layer. Slagging is a later stage of particulate fouling. If the gas-side temperature is sufficiently high for melting to occur at the surface of the particulate fouling layer, then slagging occurs (Zevenhoven-Onderwater, et al., 2000). The exhaust gas temperature in engines is not that high, hence only fouling occurs and no slagging.

The particle size distribution (PSD) of the particles in the flue gases plays an important role for the growth rate and the various stages of particulate fouling. During combustion, aerosols, i.e. submicron particles, are produced in addition to coarse particles. The produced aerosols are usually of spherical shape because of the evaporation-condensation processes which takes place. This will be described in the next section. The stages of particulate fouling are illustrated in Fig. 7, as stated by Abd-Elhady et al. (2005b). The fouling layer thermal resistance  $R_f$ , expressed in  $[m^2K/W]$ , is related to its thermal conductivity  $k$  and thickness  $\delta$  by

$$R_f = \frac{\delta}{k}. \quad (1)$$

The change in the fouling layer thermal resistance with time indicates the growth rate of the fouling layer. At the beginning of operation (a) the heat exchanger tubes are clean and the fouling layer growth is slow. The initial deposit layer (b) is likely to consist of fine particles which are transported by the mechanism of thermophoresis (Rosner, 1980; Wagoner and Yan, 1991). Due to the temperature gradient between the combustion gas and the heat exchanger surface, the particles in the flue gas experience a force in the direction towards the cooler surface. This so-called thermophoretic effect augments the conventional mass transport of sub- to micrometer particles towards the heat exchanger surface. The velocities with which the particles arrive at the surface due to thermophoresis are low, and, therefore most of them stick to the surface. This thin initial layer then grows as a result of the collection of larger particles (c), which are transported mainly by inertial impaction, Israel and Rosner (1983). As calculated by van Beek et al. (2001), the transport rate by inertia is at least one order of magnitude larger than by thermophoresis. This does not imply that transport by impaction causes a higher fouling rate than thermophoresis. Particles that are transported by impaction hit the heat

exchanger surface with a velocity larger than the one by thermophoresis, which can cause the particles to bounce off or even remove other particles from the fouling layer. The interaction between the incident particles and the deposit is an important issue for modelling the growth rate of particulate fouling and needs further study.

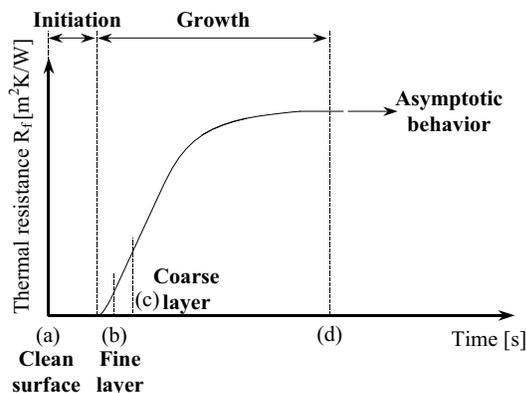


Fig. 7. Stages of particulate fouling. Adopted from Abd-Elhady et al. (2005b).

As the coarse particulate layer continues to grow (d), the thermal resistance of the layer continues to increase. During the development of this particulate layer, the temperature difference over the deposit and, therefore, the temperature of its surface will continuously increase, Senior (1987). If the surface temperature of the fouling layer becomes higher than a certain limit, which is known as the minimum sintering temperature (Al-Otoom et al., 2000), sintering takes place. The minimum sintering temperature is usually considerably below the melting point of the fouling layer material (Skrifvars and Hupa, 1992; Kuczynski, 1949). Sintering leads to the reduction of the void volume and reinforcement of the contact bridges between the particles of the fouling layer, Ristic (1979), and is therefore responsible for strengthening of the fouling layer as has been measured by Skrifvars et al. (1994 and 1998). The degree of sintering depends on the gas-side temperature and sintering time as was examined and presented by Wall et al. (1993). At this stage (d) where sintering has already started, a steady-state may develop during the deposit growth. This steady-state of deposit growth is known as the asymptotic behaviour of particulate fouling and it is shown by the horizontal arrow in Fig. 7. The asymptotic behaviour has been reported by many researchers in different applications, e.g. in EGR coolers (Zhan et al., 2008), waste incinerators (van Beek et al., 2001) and in coal-fired power plant (Bott, 1988). The main reason behind the asymptotic behaviour is sintering of the fouling layer as has been explained by Abd-Elhady et al. (2007): Sintering of a fouling layer lowers significantly the ability of an incident particle to stick to the fouling layer or to remove particles out of the layer. Also, the removal of newly deposited particles on a fouling layer due to incident particles becomes easier as sintering takes place. Accordingly, sintering reduces the fouling rate in heat exchangers by lowering the deposition rate of new

particles and by increasing the removal rate of newly deposited particles.

### 3. ANALYSIS OF DEPOSIT LAYER

#### a- Size of Particles in Diesel Exhaust Gases

Kittelson (1998) categorized aerosol size distributions of diesel engine exhaust according to three distinct modes, namely nucleation, accumulation and coarse mode. Nucleation mode particles typically range in diameter from 3 to 30 nm, and are composed primarily of volatile organic and sulfur compounds. The accumulation mode contains most of the mass and ranges in size from 30 to 500 nm. It is composed primarily of carbonaceous agglomerates and adsorbed material. The coarse mode consists of particles larger than 500 nm and contains 5–20% of the mass. These relatively large particles are formed by re-entrainment of particulate matter, which has been deposited on cylinder and exhaust system surfaces. Operating conditions such as temperature and dilution rate may change the number concentration in the nuclei mode by an order of magnitude or more (Kittelson, 2006). On the other hand, accumulation mode particles, composed primarily of carbonaceous agglomerates and ash, are formed during combustion, and are less influenced by the dilution conditions. The presence of a large accumulation mode will act to suppress the formation of the nuclei mode because the carbonaceous agglomerates scavenge volatile material, thus reducing the likelihood of gas-to-particle conversion (Khalek et al., 2000).

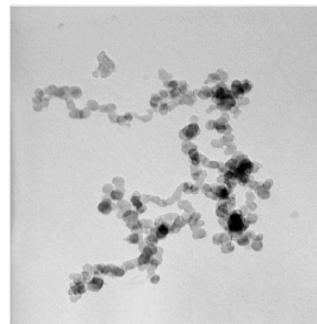


Fig. 8. TEM high-magnification images illustrating aggregate structure of individual particulates from the engine (Neer and Koylu, 2006).

Neer and Koylu (2006) investigated particulate emissions at the exhaust of a diesel engine at different engine loads and speeds by rapid thermophoretic sampling followed by direct transmission electron microscope (TEM) visualization. Figure 8 is a high magnification TEM image to identify the detailed structure of a typical diesel particulate. As can be seen, many particles agglomerated to form clusters of fractal-like geometry. The particles had nearly uniform diameters, in contrast to aggregates, which had a broad size distribution. The average diameter of the particles ranged from 20 to 35 nm for all engine loads, which is in agreement with previous studies that quantified the diameter of PM in diesel exhaust (Park et al., 2004; Wentzel et al., 2003). Lee et al. (2002) and Zhu et al. (2005) measured the average diameter of PM in two

different diesel engine exhausts as a function of load and found that average particle diameters are  $d_p = 28 - 34$  nm and  $d_p = 19 - 33$  nm, respectively.

Lepperhoff and Houben (1993) investigated deposits on EGR coolers and noted that the deposits at areas of low temperature, i.e. lower than 200 °C, contained dark materials including carbon black, wet HC and tar-like portions. The critical surfaces of an EGR cooler are cooled by engine coolant and would not be expected to be much hotter than 110 °C. Diesel exhaust contains a wide range of hydrocarbon and hydrocarbon-derived species. These include unburned and partially burned fuel and lube oil. Some of these compounds can condense on cooler surfaces. Condensation occurs when the surface of the cooler is below the dew point for the partial pressure of the compound. Thus, heavier species and higher concentration species will condense preferably. The downstream of an EGR cooler installed in a VW Passat engine is shown in Fig. 9, demonstrating the strong fouling tendency. The fouling layer shown in Fig. 9 is a black structure with a significant moisture content and a thickness of about 1.0 cm. At temperatures between 250 and 300 °C, nearly dry porous soot or tar-like deposits are seen. Above 300 °C, different light deposit colors are typically seen in a very thin layer. These are mainly inorganics from fuel and lube additives.

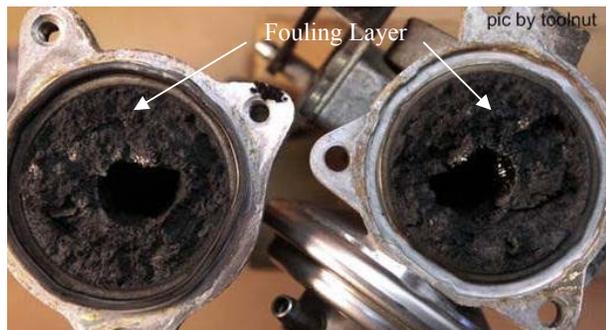


Fig. 9. Downstream of an EGR cooler (VW Passat).

#### 4. MITIGATION TECHNIQUES AND LIMITATIONS

##### 4a. Influence of Gas Velocity

Bravo et al. (2007) measured the variation of the fouling resistance in an EGR cooler as a function of gas velocity in a test vehicle. The results are presented in Fig. 10. As it can be clearly seen, the fouling resistance decreases with increasing gas velocity. Bravo et al. (2007) concluded from their experiments that the observed increase of the fouling resistance  $R_f$  in the EGR cooler may be due to both, decrease in gas flow velocity which is an already known fact (Kakac and Liu, 1988) and flow maldistribution.

Grillot and Icart (1997) introduced a mass accumulation probe into a diesel exhaust gas stream and monitored the fouling behaviour of the probe. From their experiments it can be concluded that increasing the gas-side temperature while keeping the gas velocity constant results in reducing the final fouling layer thermal resistance and decreasing the fouling rate. Removal of particles from

sintered fouling layers during operation of heat exchangers can be achieved either by shear flow as has been studied by Cabrejos and Klinzing (1992) and Al-Hayes and Winterton (1981) or by incident particle impact as shown by Werner and Haf (1988). Müller-Steinhagen et al. (1988) and Grillot and Icart (1997) have shown that when the gas velocity is increased particulate fouling is reduced. Particulate fouling can be avoided if the gas velocity is above a critical flow velocity (Abd-Elhady et al., 2004) which is defined as the main stream velocity above which rolling of the deposited particles occurs. The fouling layer hardens in time due to sintering, and can become strong enough off-set removal of particles by fluid shear, as found by Frederick et al. (2003, 2004), Barnhart and Williams (1956) and Senior (1987). Therefore, increased gas flow velocity should be adjusted the beginning of operation and not after sintering has taken place. The critical flow velocity is calculated for carbon particles as a function of the particle size, and the results are shown in Fig. 11. It can be seen that the critical gas velocity decreases strongly with increasing particle size, and that for nano-particles this gas velocity is so large that it can hardly be achieved in practice.

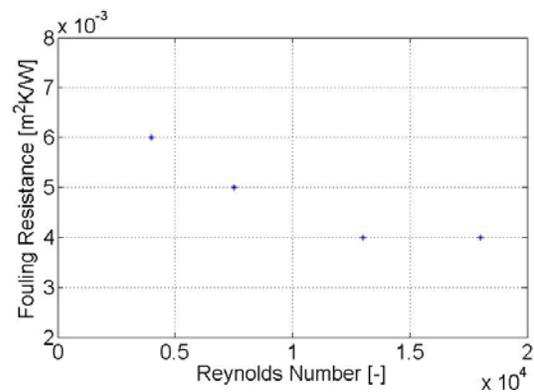


Fig. 10. Asymptotic fouling resistance in an EGR cooler as a function of Reynolds number (Bravo et al.2007).

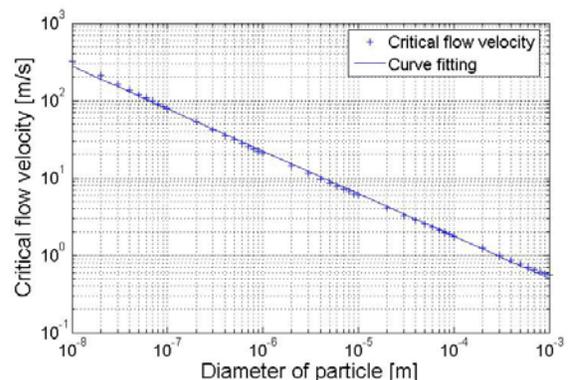


Fig. 11. Critical flow velocity for carbon particles versus particle diameter.

##### 4b. Catalyst Addition

Another method for improving the performance of EGR coolers is using an oxidizing catalyst. The function of

the catalyst is to oxidize the soot particles and the unburned hydrocarbons such that the by-products can easily evolve with the exhaust gases. Hoard et al. (2007) examined the effect of an oxidizing catalyst upstream of an EGR cooler and compared the performance of the EGR cooler with and without catalyst. Hoard et al. (2007) found that in both cases the cooler effectiveness dropped exponentially, as shown in Fig. 12, by roughly 15-20 % from clean to dirty. Zhan et al. (2008) tested a diesel oxidation catalyst (DOC) with an uncoated wall flow diesel particulate filter (WF-DPF) before an EGR cooler. The EGR cooler was connected to a 7.3 Liter V8 diesel engine, such that the exhaust from the engine is passed to a DOC, then to a WF-DPF, and eventually through the EGR cooler before exiting. Diesel particulate filters consist of a porous substrate that permits gases in the exhaust to pass through but traps the particulate matter (PM). Diesel particulate filters are very efficient in reducing PM emissions, achieving typical PM reduction in excess of 90 %, LeTavec et al. (2002). However DPF require regeneration, i.e. burning off the accumulated PM, and to achieve this, usually a DOC is used. A DOC reduces the CO, HC and PM concentration through catalytic oxidation. Zhan et al. (2008) concluded from their experiment that fouling was virtually undetected in the EGR cooler under these conditions, and that both the pressure drop across the EGR cooler and the cooler effectiveness remained constant throughout the 45 hours of the test. However, DOC and DPF are quite expensive and installing them into a diesel engine can introduce a substantial pressure drop that can influence the efficiency of the engine (Leet et al., 1998; Van Aken et al., 2007; Lundqvist et al., 2000). Using a DOC with a DPF before an EGR cooler to prevent fouling has not been realized in practice, and is still a point of further research.

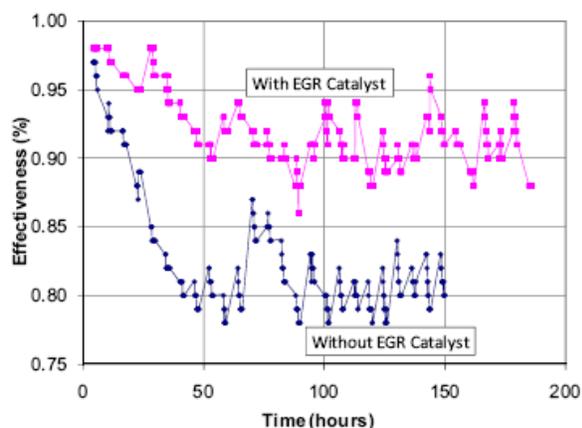


Fig. 12. EGR cooler system effectiveness versus engine running hours, without and with an EGR catalyst. Data from Hoard et al. (2007).

## CONCLUSIONS

The literature survey presented in this paper highlights various aspects related to the operation of EGR coolers in diesel engines which are installed to achieve compliance

with emissions regulations. In particular, fouling of EGR coolers introduces a very significant uncertainty into the design and operation of this equipment. Different fouling mechanisms such as particulate, sedimentation due to gravity and spinning and solidification may also be responsible. However the contribution of each of these individual fouling mechanisms is still unknown. Several mitigation techniques have been proposed to minimize fouling of EGR coolers, but so far none of them is capable of preventing fouling or keeping it at a reasonable level. Increasing the gas velocity in the EGR coolers, preventing excessive cooling of the exhaust gasses across the cooler especially at the beginning of operation and usage of DOC together with DPF seem to be promising ways of reducing particulate fouling. However, the applicability of such methods still needs to be investigated.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of General Motors, USA as well as contributions of Dr A. Knafl and Mr P.G. Szymkowicz of GM towards the preparation of this work.

## NOMENCLATURE

|                 |  |
|-----------------|--|
| BSFC            | Brake specific fuel consumption                      |
| CO              | Carbon monoxide                                      |
| DOC             | Diesel Oxidation Catalyst                            |
| DPF             | Diesel Particulate Filter                            |
| EGR             | Exhaust Gas Recirculation                            |
| HC              | Hydrocarbon  |
| NO <sub>x</sub> | Nitrogen oxides                                      |
| PM              | Particulate Matter                                   |
| TEM             | Transmission Electron Microscope                     |
| WF              | Wall Flow  |
| d <sub>p</sub>  | Particle diameter, m                                 |
| U               | Main stream velocity, m/s                            |
| R <sub>f</sub>  | Fouling layer thermal resistance, m <sup>2</sup> K/W |
| k               | Thermal conductivity, W/mK                           |

## Greek symbol

|   |                            |
|---|----------------------------|
| δ | Fouling layer thickness, m |
|---|----------------------------|

## Subscript

|   |               |
|---|---------------|
| p | particle      |
| f | fouling layer |

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