

Diesel EGR Cooler Fouling

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ABSTRACT

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 and thus may degrade engine efficiency under some operating conditions.

It is unlikely that EGR cooler deposits can be prevented from forming when soot and HC are present. The presence of cooled surfaces will cause thermophoretic soot deposition and condensation of HC and acids. While this can be affected by engine calibration, it probably cannot be eliminated as long as cooled EGR is required for emission control. It is generally felt that "dry fluffy" soot is less likely to cause major fouling than "heavy wet" soot. An oxidation catalyst in the EGR line can remove HC and has been shown to reduce fouling in some applications. The combination of an oxidation catalyst and a wall-flow filter largely eliminates fouling.

Various EGR cooler designs affect details of deposit formation. It is generally thought that fin type coolers, having large surface area, are less impacted by fouling than tube-in-shell type coolers. However, both types are subject to significant fouling and the choice of type is often made more by package considerations than by deposit performance. High gas velocities tend to reduce deposition although they lead to large pressure drop.

Cooler deposits tend to stabilize after long operating time, often 50-200 hours. The mechanisms leading to this stabilization are not clearly understood. There may be deposit removal mechanisms, or it may be that the rate of deposition decreases as deposits build (or both).

INTRODUCTION

EGR coolers are used on diesel engines to reduce intake charge temperature, resulting in cooler combustion temperatures while maintaining desired air/fuel ratios, thus reducing NOx emissions. They 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 will require increased EGR flow rates and reduced temperatures. This is likely to lead to deposition of soot, hydrocarbons, and acids in the EGR cooler. These deposits

- reduce heat transfer capacity thus increasing charge temperature and emissions
- increase pressure drop across the cooler, which can degrade fuel efficiency due to increased pumping work
- are quite acidic and may cause corrosion

This paper is an attempt to gather the information available in literature. What are the deposits and how do they occur? What can be done to prevent them or at least mitigate their effects? What are the main unknowns that require further research?

Most current diesel engines have a single EGR cooler, using engine coolant to cool the EGR. Some engines have more than one cooler; this is primarily driven by the amount of cooling required and the package space available. Some manufacturers have discussed plans for future engines to have more effective cooling by use of a second cooler and a second cooling system. Here, coolant can be supplied at 40-50°C so that the EGR outlet temperature can be reduced further than could be done with the normal cooling system.

Another choice in the EGR system is between high-pressure and low-pressure EGR loops. In a high-pressure loop, EGR is taken from the exhaust upstream of the turbocharger turbine, and the cooled gas is 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 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 operates at essentially atmospheric pressure. A number of papers have discussed reasons for choosing high- or low-pressure loop (11, 12, 13). Of direct importance to cooler deposits, a low-pressure loop EGR system can take EGR from downstream of the aftertreatment 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. For the remainder of this paper, we will assume high-pressure loop EGR unless otherwise noted.

HEAT EXCHANGER BASICS

Heat exchangers are generally categorized based on flow arrangement and type of construction. The simplest form of heat exchangers are concentric tubes called double pipe heat exchangers in which flow arrangement can be parallel or counter flow. Cross flow heat exchangers are another form that can be finned or unfinned heat exchangers. Another common heat exchanger is shell-in-tube which differs according to the number of tube passes and shell passes. The most complex category is compact heat exchangers which have a large heat transfer surface area per unit volume.

An important parameter in heat exchanger analysis is determination of the overall heat transfer coefficient which is calculated in according to conduction and convection resistance between the hot and cold fluids. The general form of this coefficient can be expressed as (36):

$$\frac{1}{UA} = \frac{1}{U_c A_c} = \frac{1}{U_h A_h}$$

$$= \frac{1}{(\eta_0 h A)_c} + \frac{R_{f,c}''}{(\eta_0 A)_c} + R_w + \frac{R_{f,h}''}{(\eta_0 A)_h} + \frac{1}{(\eta_0 h A)_h}$$

Where:

c, h : Cold and hot fluids, respectively
 A : Heat transfer surface area
 h : Convection heat transfer coefficient

R_w : Conduction resistance of wall separating cold and hot sides

R_f'' : Fouling factor

η_0 : Overall surface efficiency of a finned surface and defined as

$$\eta_0 = 1 - \frac{A_f}{A} (1 - \eta_f)$$

Where:

A_f : Entire fin surface area

η_f : The efficiency of a single fin and defined as

$$\eta_f = \frac{\tanh(mL)}{mL}$$

$$m = (2h/kt)^{1/2}$$

Where:

t : Fin thickness

k : Thermal conductivity of the fin

By developing analytical solutions for simple geometries, the heat transfer coefficients of hot and cold sides can be obtained. In general, the non-dimensional form of heat transfer coefficient, called the Nusselt number, can be expressed as a function of Reynolds and Prandtl number.

$$Nu = \phi_1(Re, Pr)$$

$$Pr = \frac{\nu}{\alpha}$$

$$Re = \frac{VD_h}{\nu}$$

Where:

ν : Kinematic viscosity

α : Thermal diffusivity

V : Velocity

D_h : Hydraulic diameter

In general, we need a characteristic length to define the Reynolds number. In most cases, hydraulic diameter is selected in heat exchanger analysis. Also, the definition of hydraulic diameter depends on the geometry and a complete list of it can be found in the text books.

L/D is another parameter that can be included in definition of the Nusselt number, although for most heat exchangers the length effect on the heat transfer coefficient is negligible. For simple geometries like double pipe heat exchangers while the flow is fully developed, there are several equations for Nusselt number according to Reynolds number (laminar or turbulent flow) and Prandtl number (37).

If there is any mass transfer involved in the heat exchanger design, another non-dimensional number called Sherwood number is required in the analysis. Sherwood number is defined as

$$Sh = \phi_2(Re, Sc)$$

$$Sc = \frac{\nu}{D}$$

Where:

Sc : Schmidt number

D : Mass diffusivity

There is an analogy between mass and heat transfer but in most cases in heat exchanger analysis, there is no mass transfer between hot and cold sides.

Two measures of cooler performance are commonly used:

- Effectiveness is defined as the fraction of the maximum possible heat transfer that is achieved. The inlet coolant is the lowest possible outlet gas temperature. The equations below show the case for constant mass flow of coolant and gas; here, simple temperature measurements can be used to calculate effectiveness. If the gas is cooled all the way to coolant inlet temperature, then effectiveness is 100%.

$$\varepsilon = \frac{q_{actual}}{q_{max}}$$

$$= \frac{T_{gas\ in} - T_{gas\ out}}{T_{gas\ in} - T_{coolant}}$$

- Pressure drop across the cooler is also an important factor. As deposits build, pressure drop increases partially due to physical blockage of the gas flow passages, and partially due to the fact that the exhaust gas remains hotter (and thus larger volume) longer when the surface is dirty.

It will be helpful to have an idea of some typical values for a modern diesel EGR cooler system. The following would be common for an engine of about 6.5 L displacement:

- Reynolds numbers in the cooler passages are typically from around 500 at low flow to above 3500 at a design point. Thus, flow may be laminar or turbulent.
- Average gas flow velocities are generally in the range 20-30 m/s maximum in the cooler
- Heat transfer surface area for EGR coolers is about 0.5-0.6 m²

Zhang et.al (16) show a number of useful graphs illustrating EGR cooler performance. These are from their system which used simple straight-tube coolers in diesel exhaust with coolant approximately 20°C. Further details are in the reference; the following figures are shown here only for general reference. Figure 1 shows temperature drop across an EGR cooler versus mass flow rate for various inlet gas temperatures ranging from 250°C (lowest curve) to 400°C (top curve). Figure 2 shows heat flow versus mass flow, again for various inlet gas temperatures. Figure 3 shows Nusselt number versus Reynolds number for various inlet gas temperatures. Figure 4 shows effectiveness versus Reynolds number.

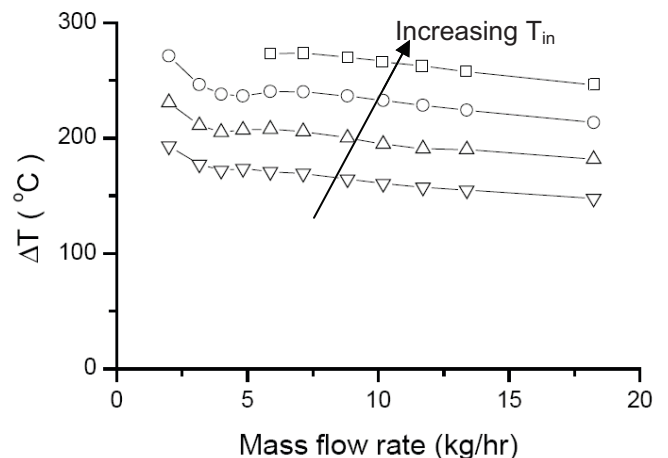


Figure 1 Temperature drop across an EGR cooler versus flow rate for different inlet temperatures ranging 250°C to 400°C (16)

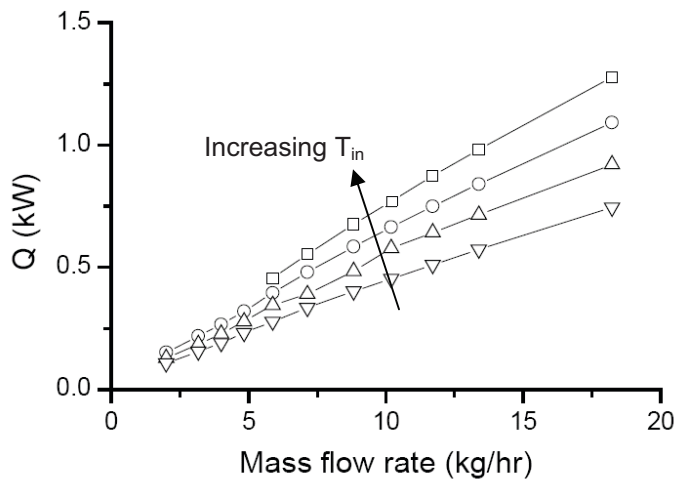


Figure 2 Heat flow from exhaust through an EGR cooler versus mass flow for different inlet gas temperature (16)

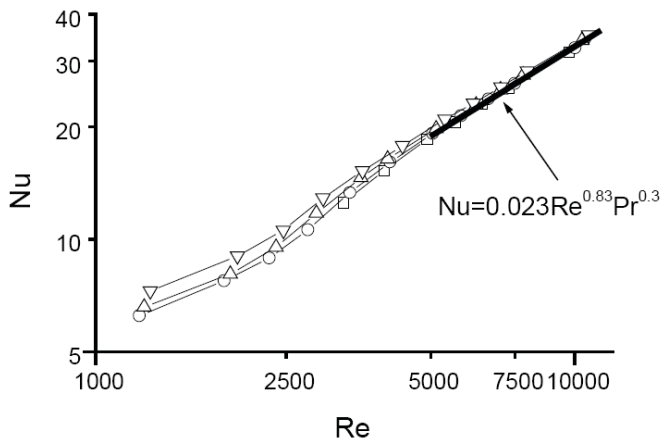


Figure 3 Nusselt number versus Reynolds number for the same cases (16)

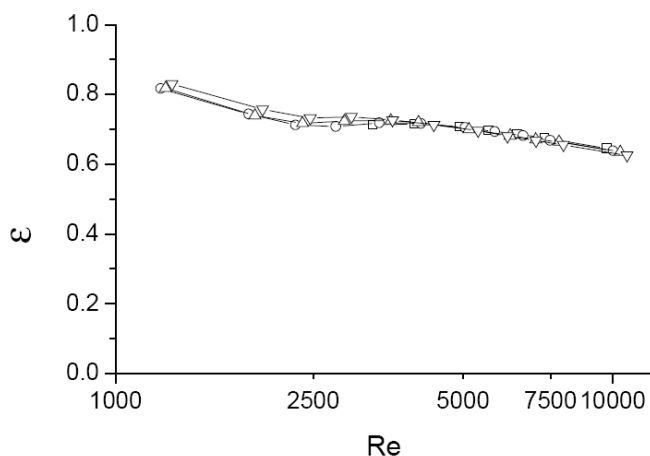


Figure 4 EGR Cooler effectiveness versus Reynolds number (16)

IMPORTANCE OF EGR COOLER DEPOSITS

EGR is cooled in order to improve emissions. Kowada et.al. (41) show data for an engine tested with a base EGR cooler and with an improved cooler with improved

cooling capacity, Figure 5. With better charge cooling, the engine produces much lower NO_x and slightly lower PM (smoke) with no loss in BSFC. For these reasons, cooler EGR is very desirable in diesel engines when lower emissions are required.

As deposits build in the EGR cooler, they form a layer that adds thermal resistance (or reduces thermal conductivity) between the coolant and the hot exhaust gas. Figure 6 from Bravo et.al. (1) shows the loss of EGR cooler effectiveness versus mileage in vehicle testing. It can be seen that as deposits build the coolers become less effective. Although some coolers suffer only a small loss, some lose over 30% of their cooling. The same paper shows that the degree of degradation versus mileage is not a normal distribution. In order to pass in-use emissions, it is necessary for the vehicle to meet the required emission control targets with the worst-case field condition; thus, EGR coolers must be over-sized on the order of 30% to obtain required cooling efficiency when dirty.

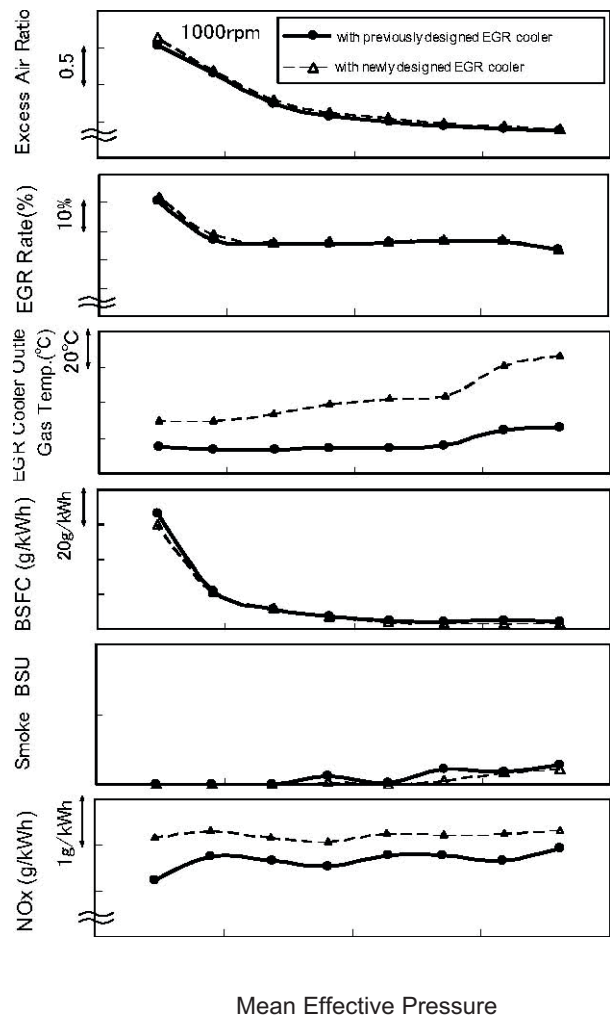


Figure 5 Effects of cooled EGR on engine operation. Dashed line: base EGR cooler. Solid line: EGR cooler with increased cooling capacity. From (41).

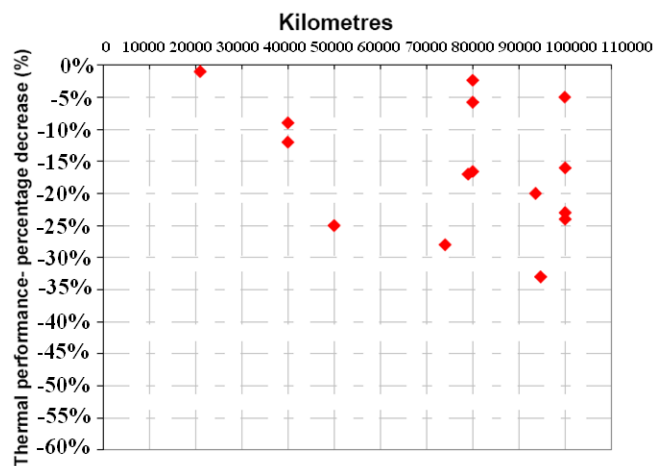


Figure 6 Loss of EGR cooler effectiveness versus mileage in vehicle testing. From SAE 2005-01-1143 (1).

Another example of cooler degradation is shown in Figure 7. Here, a 2008-level diesel engine having two EGR coolers in series is run on a three mode cooler fouling test, and the cooler effectiveness is plotted versus time. Two conditions are shown: in the upper curve, the EGR system has an oxidation catalyst upstream of the cooler, while in the lower curve there is no EGR catalyst. In both curves, the cooler effectiveness drops on a roughly exponential curve, reaching a steady state value at lower effectiveness than clean. At the condition shown, effectiveness drops roughly 15-20% from clean to dirty.

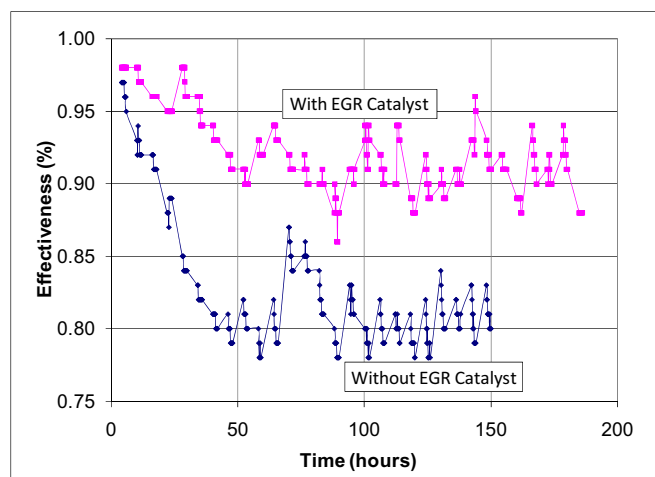


Figure 7 EGR cooler system effectiveness versus engine running hours, without (below) and with (above) an EGR catalyst. Data from Hoard et.al. (2).

Figure 8 shows the exhaust temperature at the exit of the second EGR cooler versus time, for the same experiments as Figure 7 (data courtesy of the authors of that study). When clean, the coolers lower exhaust gas temperatures to within 25°F of the inlet coolant temperature. The outlet temperature increases significantly as deposits build. Unfortunately, no pressure drop data were available in this data set.

Zhan et.al. (40) tested fouling of full-scale EGR coolers with various exhaust treatment devices located upstream of the cooler. In the Base case they used uncoated catalyst and flow through substrate. In the case labeled "DPF" below, an uncatalyzed wall-flow filter was used along with a DOC catalyst. Figure 9 shows the EGR temperature at the exit of the cooler versus time for these two cases (the paper included other cases that were left out of the redrawn figures here). The outlet temperature is nearly constant when the gas treatment has removed soot and HC from the exhaust.

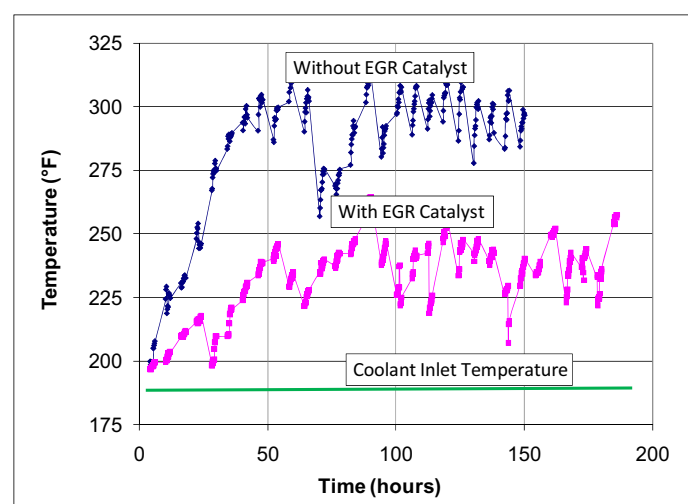


Figure 8 Temperature at second cooler outlet without (top) and with (middle) an EGR catalyst, and coolant inlet temperature (bottom). Data from the same study as Figure 7.

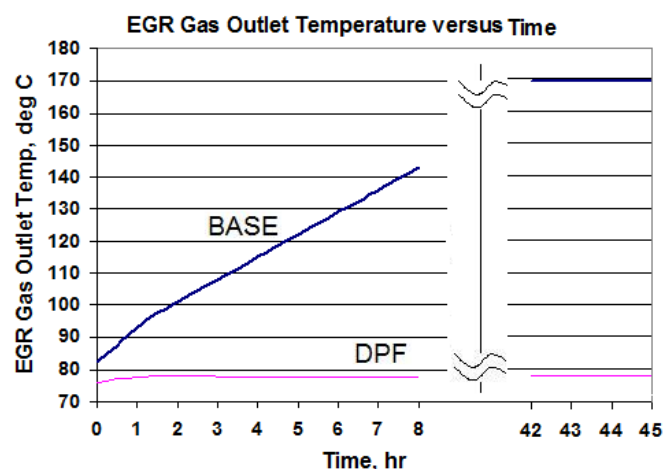


Figure 9 EGR gas temperature at cooler outlet versus time for base and filtered exhaust. EGR inlet temperature was constant at ~500°C and coolant inlet temperature was 60°C. Redrawn from (40).

Figure 10 shows pressure drop across the EGR cooler (gas flow 167 kg/hr) for the same two cases. Deposit build significantly increases the cooler pressure drop for the base case. Of course, the wall flow filter has its own

pressure drop; Figure 11 shows the combined pressure drop of DOC, filter, and cooler versus time. Although pressure drop is higher initially with the filter, in only a few hours the base case becomes worse. Note that these authors do not address issues related to DPF regeneration or soot accumulation in the filter. These experiments demonstrate that cooler fouling is indeed related to soot and/or HC since removing both allows the cooler to maintain nearly-clean performance.

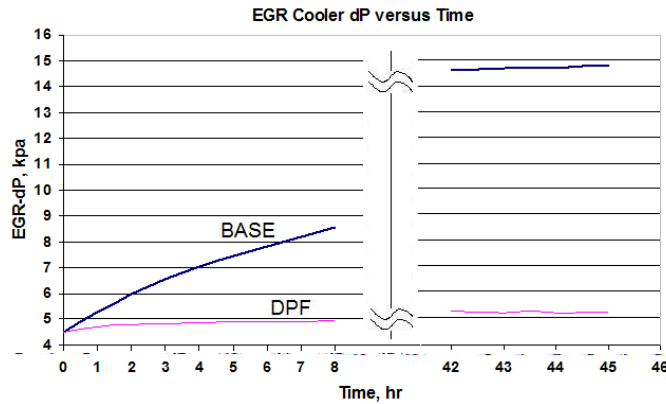


Figure 10 Pressure drop across EGR cooler (only) versus time for base and filtered EGR. Redrawn from (40)

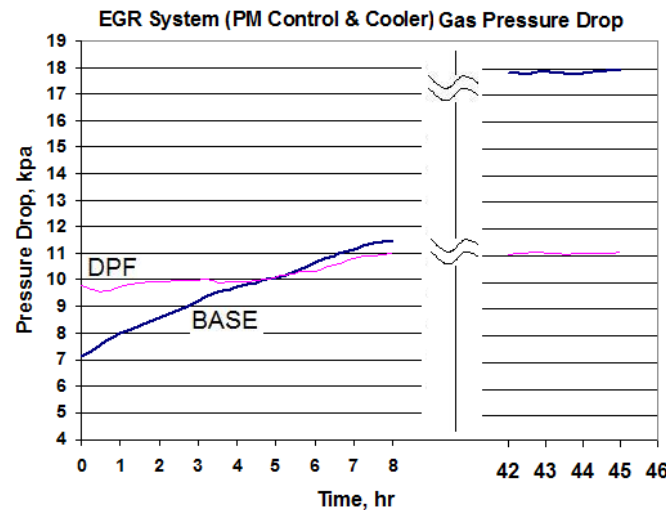


Figure 11 Pressure drop across EGR cooler and filter versus time for base and filtered EGR. Redrawn from (40)

Hesselgreaves (17) notes that coolers are generally oversized to allow for the effect of fouling. However, in some cases the larger the cooler is the lower the velocities and thus the worse the fouling tendency. Pressure drop is often the limiting factor in choosing a compact heat exchanger.

Leet et.al. (11) tested a low pressure loop EGR system. They found that after aging, the deposits in the charge air cooler increased its pressure drop by 15% and degraded heat transfer by 8%.

WHAT ARE DEPOSITS?

The deposits in the EGR cooler form a layer on the cooled surfaces, Figure 12. Here, deposits are shown after 200 hours of an EGR cooler fouling engine dynamometer test. The figure shows the inlet of the first EGR cooler. The deposits are black, and in this case fairly dry and fluffy in appearance. There is some evidence of flaking of the deposits, although it cannot be said with certainty whether this occurred while the engine ran or during handling and cutting.



Figure 12 Deposits at EGR cooler inlet following 200 hour engine fouling test (2).

Cooler deposits can also have a wet, oily appearance or in some cases can be hard and brittle in character. These differences evidently arise depending on the relative quantities of elemental soot PM, HC, acids, and perhaps the time-temperature history. These issues will be discussed in more detail in following sections.

Lepperhoff and Houben (3) note that engine deposits (general deposits, not diesel EGR coolers specifically) are a combination of organics including carbon, HC, oxygen, and nitrogen, along with inorganics including sulfur and traces of barium and calcium. They further note that in areas of low temperature ($<200^{\circ}\text{C}$) dark material including carbon black, wet HC portions and tar-like portions are visible. At temperatures between 250 and 300°C , nearly dry porous soot or tar-like deposits are seen. When a lacquer coating is seen they say it is related to lube oil. Above 300°C , different light deposit colors are seen typically in a very thin layer. This is mainly inorganics from fuel and lube additives. Note that in an EGR cooler, the critical surfaces are cooled by engine coolant and would not be expected to be much hotter than 110°C .

Some researchers including Siegel & Zinbo (4) characterize the deposits by use of thermogravimetric analysis (TGA). In these experiments, a sample of the deposit is heated and the weight change versus temperature recorded. The heating may be done in air or in an inert gas like nitrogen or helium. When heating