EFFECTS OF SOOT DEPOSITION ON EGR COOLERS: DEPENDENCY ON HEAT EXCHANGER TECHNOLOGY AND ENGINE CONDITIONS

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ABSTRACT

Durability of EGR Cooler performance is a key issue that affects the function of EGR system as anti-pollutant device. There is a significant concern to guarantee function of these devices during the useful life of the vehicle. Decrease of thermal efficiency and increase of gas pressure drop caused by soot deposition implies higher EGR gas temperature and lower EGR gas flow. Selection of the heat exchanger technology and definition of design parameters have an important effect on this degradation. Moreover the understanding of critical engine operation conditions enables to establish recommended use constraints. This paper reviews a compendium of different tests, where different technologies and sizes of EGR coolers have been exposed to different engine test cycles. It concludes with indications for EGR Cooler dimensioning and some considerations on use conditions. Experience with these tests show how EGR Cooler function should be reported and settle basis for future research projects.

INTRODUCTION

Legislation for vehicles imposes more and more severe constraints regarding gaseous emissions to the environment. Apart from CO_2 restrictions, which are related to optimization of engine operation through increase of its efficiency, the pollutants that are limited are the following: CO, HC, NO_x and PM (particulate matter). Evolution of standards in the European Union shows the challenge that car manufactures must face for coming years (table 1), in particular for passenger cars equipped with diesel engines.

Table 1. EU Emission Standards for Passenger Cars (category M1 – for Euro5/6 vehicle mass not exceeding 2610 kg) / Diesel engines.

Stage	Year	CO	HC	HC+NO$_x$	NO$_x$	PM
		g/km				
Euro 1	1992	2.71	-	0.97		0.14
Euro 2	1996	1	-	0.7		0.08
Euro 3	2000	0.64	-	0.56	0.50	0.05
Euro 4	2005	0.5	-	0.30	0.25	0.025
Euro 5	2009	0.5	-	0.23	0.18	0.005
Euro 6	2014	0.5	-	0.17	0.08	0.005

Exhaust after-treatment for gasoline engines enables to reach limit values with the use of the well-known three-way catalyst. But due to the fact that diesel engine is operating with excess of air, it is not possible to introduce reduction chemical processes in the exhaust similarly. Thus, typical after-treatment in diesel engines consists of DOC (Diesel Oxidation Catalyst) and DPF (Diesel Particle Filter) to reduce CO, HC and PM emissions. The EGR (Exhaust Gas Recirculation) system provides reduction of NO_x emissions in source. Basically, it consists of introducing a part of burnt gas to the combustion chamber in order to reduce temperature and pressure, thus avoiding formation of this pollutant. The most usual system consists of an EGR valve and an EGR cooler. The use of the system, that is the engine regime and load where it operates, is determined by homologation cycles of the vehicles. In particular, the NEDC (New European Driving Cycle) test cycle is used for European Union approval of emissions and fuel consumption for light duty vehicles (EEC Directive 91/C81/01). The entire cycle includes four ECE (city cycle) and one EUDC (Extra Urban Driving Cycle).

More severe values for NOx emissions have led to introduction of alternative and complementary after-treatment devices, such us SCR (Selective Catalytic Reduction) and LNT (Lean NO_x Trap). So far application of these devices has been more common for medium and heavy duty applications. However, the significant decrease of limit levels for NO_x in following standards has spread their use also for light duty applications (passenger cars). It is foreseen that both in-source and after-treatment will be used for future applications.

As for the EGR system, impact of soot deposition is a known issue affecting its operation. On one hand, there is an effect on durability of the function for the EGR valves. These valves are located in the EGR line. Their function determines de EGR percentage, that is, the ratio of burnt gases that are recirculated and mixed with the fresh air entering the combustion chamber. Continuous exposure to exhaust gases can give rise to blocking of mobile elements due to soot deposition in functional parts. On the other hand, the soot layer in the EGR cooler causes the degradation of performance of this heat exchanger. The EGR cooler is located in the EGR line in order to further reduce temperature in the combustion chamber and also to increase mass of burnt gases recirculated. The degradation of performance will give rise to a malfunction that could mean the non fulfillment of NO_x limits. Thus, it compromises also the durability of the function and moreover environmental legislation.

SOOT DEPOSITION ON EGR COOLERS

Basics

Exhaust gases from an engine contain basically CO_2, CO, H_20, H_2, CH_4, un-burnt hydrocarbons, fine soot particles and nitrogenous compounds (Abd-Elhady et al., 2011). The flow of the exhaust gas through the EGR cooler causes deposition of soot in the heat exchanger internal surfaces. The effect of this soot deposition is a fouling layer that affects both thermal efficiency and permeability of the heat exchanger. The fouling layer acts as an isolation for heat transfer, so it means and additional resistance for heat flow from hot exhaust gas to engine coolant. Moreover the thickness of this fouling layer modifies hydraulic diameter of the gas flow passages, thus giving rise to an increase in gas pressure drop for exhaust gas. The effects on the engine are different regarding thermal efficiency and permeability degradation. As for thermal efficiency, it means that exhaust gas exits from the EGR cooler to a higher temperature than for the design conditions. So, it affects mainly the temperature of the mixture burnt gas and air. It will have an impact on NO_x formation that will depend on the specific engine and vehicle application. As for pressure drop, the effect depends on at what extent this pressure drop increases. The accurate limit that can be defined for low or high pressure drop depends also on the specific application. If the increase in pressure drop is low, the EGR valve is able to compensate it by modifying position of actuator so EGR percentage is maintained in relation to design point. However, if it is not possible to open more the EGR valve, the recirculated mass flow will decrease, thus affecting also NO_x formation. Moreover some engine architectures that are provided with a throttle valve in the intake that enables increasing EGR rate could lead to excessive blocking of intake air that would lead to lack of power in the engine.

Fouling effect on EGR cooler performance has been more and more known for customers in the last years. Nowadays some of them impose degradation limits in the technical specification for this component. So, apart from heat power and permeability values for the new component, a given percentage is admitted after exposure to exhaust gases. It is assumed that fouling has an asymptotic behavior (Hoard et al., 2008; Zhang et al., 2008), so it is expected that EGR cooler supplier is able to know typical degradation of the heat exchanger.

Degradation of heat transfer can be characterized by means of the fouling resistance. So, this term is implemented in the calculation as an additional thermal resistance to add for the heat flux from one fluid to the other, that is, from exhaust gas to engine coolant. The calculation of the fouling resistance is possible once the heat exchanger calculation is done with the rest of thermal resistances known. Thus, this resistance sums up to gas side convection, conduction through walls and coolant side convection. This expression is shown below (1).

$$Rt = \frac{1}{h_{gas} \cdot Ac_{gas}} + Rw + \frac{1}{h_{coolant} \cdot Ac_{coolant}} + \frac{Rf}{Ac_{gas}} \quad (1)$$

The heat transfer impact will be calculated with the overall heat transfer coefficient as follows (2;3).

$$Rt_t = \frac{1}{U \cdot A} \quad (2)$$

$$Q = U \cdot A \cdot LMTD \quad (3)$$

In this latter equation, thermal resistance in gas and coolant side is given by convection coefficient (h), and R_w represents conduction resistance. Fouling resistance is represented by R_f**.** A simple evaluation of magnitude for the different thermal resistance results that the most important terms are gas side resistance and fouling. It must be noticed that the influence of this latter value on the overall resistance is divided by contact heat transfer area. Thus, theoretically speaking the effect of fouling can be minimized if heat transfer area is increased, that is, with the use of fins.

Heat exchanger technologies

From first introduction of EGR coolers in the market around year 2000 for Euro3 standards, technology of the heat exchanger has been evolving to fit with customer demands. These demands have been: increase of thermal efficiency and decrease of gas pressure drop. The aim is to further decrease exhaust gas temperature into the combustion chamber and also to increase the mass of EGR flow. Of course, these demands correspond to evolution of standards, following significant decreases in NO_x level from one standard to another. As shown in the table 1, the value of NO_x emissions in the NEDC cycle has decreased from 0.5 to 0.25, 0.18 and 0.08 g/km in following standards from Euro3 to Euro4, Euro5 and Euro6.

One important premise for EGR cooler is cost reduction typical for automotive applications. So, an optimum design must be made in order to achieve function requirements balanced with a competitive cost.

First designs for Euro3 applications were typical “shell and tubes” technology with round smooth tubes, as the one shown in figure 3. The exhaust gas is introduced in the heat exchanger through headers, so the gas flows into the tubes, whereas the coolant is introduced trough pipes and circulates in the housing outwardly to tubes.

Fig. 3 Typical EGR cooler for Euro3 application.

Following requirements led to use of corrugated instead of smooth tubes in order to increase thermal efficiency through turbulence. Generation of EGR cooler for Euro5 application introduced the use of rectangular corrugated tubes into rectangular housing in order to optimize volume versus performance. As for Euro6, the increase in thermal efficiency required, together with introduction of criterion for degradation linked to fouling, led to use of internal fins (tubes and fins or plates and fins applications). Of course, this is the general road-map of technology that Valeo Powertrain Thermal Systems has developed (Bravo et al., 2006). In general terms, evolution of the market of EGR coolers has followed similar trend (though introduction of fins was prior to Euro6 for some EGR coolers manufacturers).

So, generally speaking, technology with “shell and tubes” has been quite common up to Euro5 standard, whereas the use of internal fins has been generalized for coming Euro6 applications.

Figure 4 and 5 present different tubes design for Euro4 and Euro5 standards. Figure 6 presents “fin and tube” technology for Euro6.

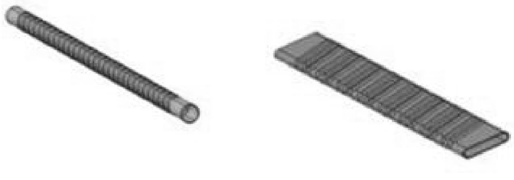

Fig 4 and 5 Corrugated round tube and rectangular tube

Fig 6 Tube with internal fin for Euro6 application

Characterization of fouling effect

Typically the evolution of heat exchanger technology for EGR cooler application has been based on performance for new status, that is, without fouling. In this case, characterization of EGR cooler performance is done in a laboratory test bench where function is characterized with clean air and coolant.

However, from the starting of EGR cooler activity, a significant effort has been done in order to characterize the fouling effect. First issue was to develop a representative test method to represent fouling found in engine bench and vehicle use (Bravo et al., 2005). Due to high cost of very long engine tests, following research activity has been focused on comparative test that try to answer to most common customer questions:

- Influence of heat exchanger technology
- Impact of different engine operation conditions

A first experiment was made for tests up to 8 hours comparing with typical stationary condition for Euro5 application and cyclic conditions (Bravo et al., 2007). In this case, to idle and intermediate speed and load of the engine, a point of high gas flow was added: 20 g/s and 420ºC for exhaust gas entering the EGR cooler.

Following experiment was done to further increase gas flow and temperature in order to follow customer demands, also for comparative tests up to 8 hours. Thus, exhaust gas conditions were fixed at 25 g/s and 520ºC. Both experiments were made for different heat exchanger technologies.

All these tests were made without significant modification of tuning of the engine, so fouling effects were dependant on specific combustion modes and EGR operation conditions of the engines used. However, different experiments with customers led to conclusion that EGR strategy can differ significantly from one application to another. What is more, future applications for Euro6 and beyond can integrate very different exposure conditions for the EGR cooler. Thus, a new set of tests was carried out in order to understand how critical conditions could affect EGR cooler performance. In this case, special attention was given to exhaust gas composition, especially for HC content and opacity index.

Thus, three different set of experiments are reviewed in the present study in order to give a comprehensive view of fouling research performance by Valeo.

RESULTS

Experiment on fouling has been carried out for HP (High Pressure) EGR configuration. That is, recirculated gases are taken before turbine and re-introduced in the combustion chamber after the compressor, according to sketch shown in figure 7.

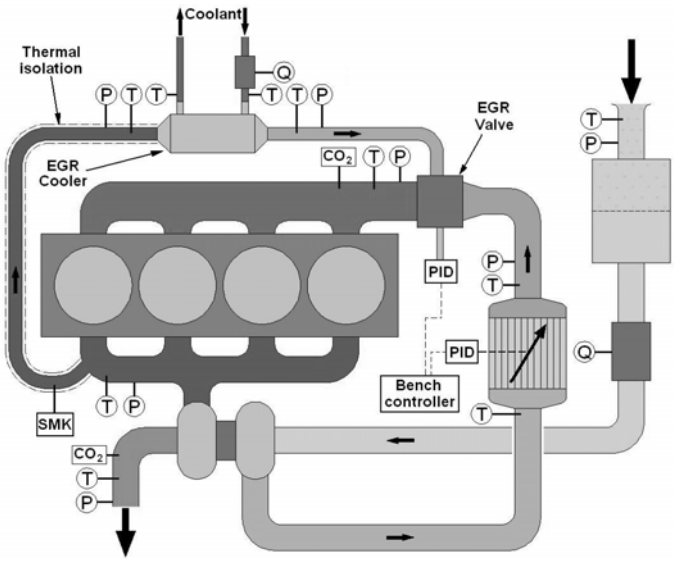

Fig. 7 Sketch of experimental facility

First set of experiments for exhaust gas conditions at 20 g/s and 420ºC, gave a characterization of fouling resistance for two different technologies: flat corrugated tube and plate and fin technology. In this condition, it was verified that the value of fouling resistance (R_f) calculated was not significantly dependent on heat exchanger technology. However, the degradation on EGR cooler function is highly dependent on heat exchanger technology. This is due to the fact that there was a significant difference in heat transfer area for the two technologies, and this difference has an important weight in the term associated in fouling for the overall thermal resistance. In the same way, bigger coolers with higher heat transfer area will suffer less impact of fouling. In the case that increase in dimensions of the heat exchanger occurs in cross section, the value of R_f has a slight dependence, obtaining lower R_f value for higher Reynolds numbers. Of course, the value of R_f is associated to a specific engine operation mode, and variations are expected for different conditions of EGR cooler use (Bravo et al., 2005). A summary of results is presented in tables 2 and 3.

Table 2. Summary of fouling effect on flat tube technology after 8-hours test for different sizes (S: reference section / L: reference length).

Flat tubes EGR Cooler Relative size	Thermal efficiency clean - fouled (%)	Thermal efficiency decrease (%)	Fouling resistance Rf (m^2.K/W)
S	85 - 70	17	0,006
S *0.5	82 - 60	26	0,005
S *0.3	77 - 54	29	0,004
S *0.5/L*0.5	69 - 41	40	0,005
S *0.25/L*2	91 - 62	32	0,004

Table 3. Summary of fouling effect on plate and fin technology after 8-hours test for different sizes (S: reference section / L: reference length).

Plate& fin EGR Cooler Relative size	Thermal efficiency clean - fouled (%)	Thermal efficiency decrease (%)	Fouling resistance R_f (m^2.K/W)
S	82 - 75	8	0,005
S *0.6	76 - 65	14	0,005
S *0.4	72 - 58	19	0,004

Second set of experiments for 8-hours was performed for exhaust gas conditions at 25 g/s and 540ºC. In this case, the fouling resistance increased slightly from a medium value in previous experiments of 0,005 to 0,006 m^2.K/W. The previous results were confirmed: lower impact in thermal efficiency for heat exchangers with fins with similar value of R_f, and lower R_f for higher gas velocity.

An analysis of different engine operation conditions was also made in the third set of experiments. Previous experiments took standard EGR conditions for Euro4 and Euro5 use, and no special care was taken about characterization of HC content. So, different engine operation conditions were tested in order to understand impact of exhaust gas composition. As for HC content, the conditions are presented in table 4 (Bravo et al., 2013).

Table 4. Conditions of tests with high HC content.

	HC (ppm)
Standard calibration	60
Operation point 1	200
Operation point 2	500

A technology with tubes and fins were characterized, with fin parameters similar to previous plate and fin technology. Measurements were taken in the engine itself to provide information also about changes on pressure drop.

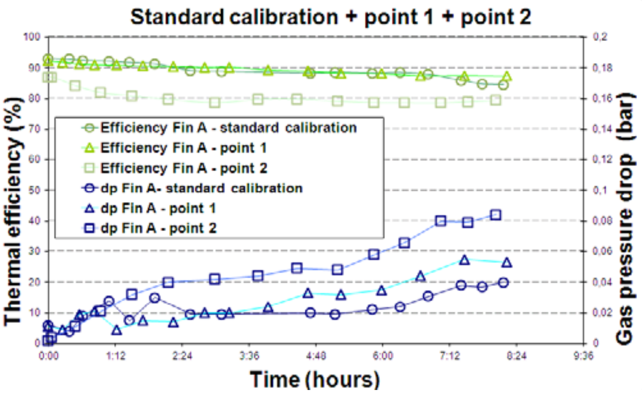

Fig. 8 Engine bench measurements for high HC content compared with standard calibration

Figure 8 shows thermal efficiency and gas pressure drop evolution during the test period of 8 hours for a standard fin (Fin A) with three different operation conditions, corresponding to table 4.

Value of Rf calculated for standard calibration was 0,005 m^2.K/W and 0,006 m^2.K/W. So, they are in good agreement with values obtained in first and second experiments. However, condition with HC content 500 ppm showed a significant increase in the fouling resistance value, up to 0,009 m^2.K/W. Besides, the increase in gas pressure drop shows a critical value for EGR function in the engine.

Also high opacity conditions was tested, as shown in table 5. Results show degradation similar to highest HC content (figure 9).

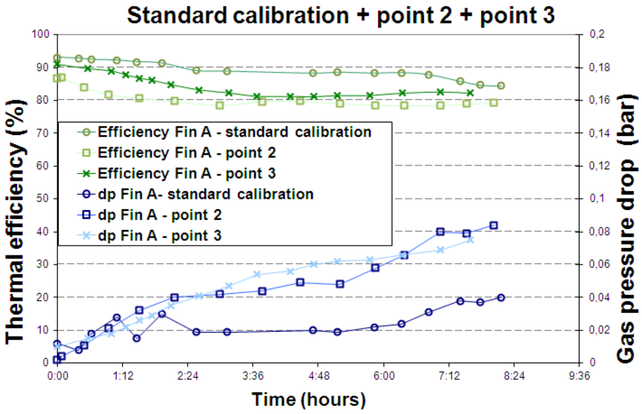

Fig. 9 Engine bench measurements for high opacity compared with standard calibration and highest HC content

Figure 9 shows thermal efficiency and gas pressure drop evolution during the test period of 8 hours for a standard fin (Fin A) with three different operation conditions, corresponding to table 4 and 5.

Table 5. Condition of tests with high opacity.

	Opacity (FSN)
Standard calibration	2
Operation point 3	3.1

DISCUSSION

Main objective to investigate on fouling effect on EGR coolers is to get a representative impact value to answer to customer demands on function durability. Thus, the values of R_f obtained have been compared with parts recovered from engine bench and vehicle tests. These parts show values between 0,002 and 0,005 m^2.K/W. For particular applications, where high HC content is suspected in customer application, a complete clogging leading to unacceptable increase in pressure drop has been achieved. This type of fouling could be similar to the one obtained for tests with high HC content of 8 hours. But customer tests are much longer in time than the ones made just for comparison reasons, so they are expected to be more critical.

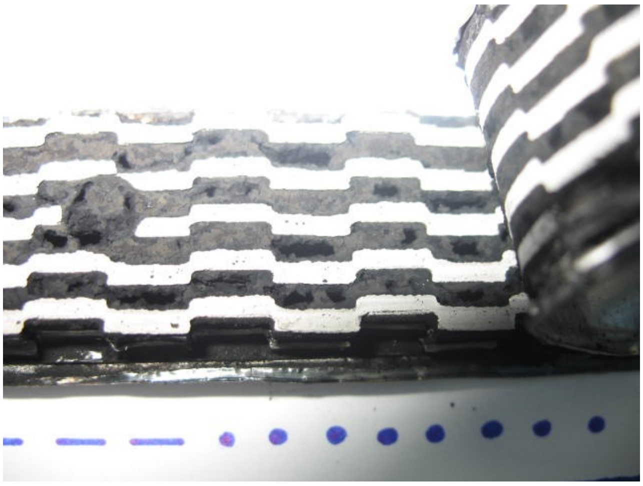

Fig. 10 Image of tube and fin heat exchanger with accumulation of soot.

There are also additional fouling modes that have not appeared in 8 hours tests. This is the case for the fouling type known as varnish. Even if high HC content has been used, fouling has the aspect of soot but not brilliant deposits. These deposits could be due to excessive oil consumption in the engine.

Soot composition has been analyzed in order to compare characterization for 8 hour controlled tests and vehicle tests.

- Analytical techniques used in this characterization include:

1) Elemental analysis for carbon, hydrogen and nitrogen quantification (% wt.).
2) Fourier Transform Infrared Spectroscopy (FTIR) is useful to analyze the presence of functional groups as well as adsorbed molecules on soot surface.

3) Thermogravimetric Analysis (TGA) up to 900 ºC in an inert atmosphere of nitrogen in order to determine mass losses due to thermal desorption and decomposition of different compounds.
4) Thermogravimetric Analysis up to 900 ºC in an oxidative environment of air for the evaluation of soot resistance toward oxidation.
5) Determination of the soot specific surface area by physical adsorption of N_2 at -196 ºC applying BET equation.
6) Gas Chromatography / Mass Spectroscopy (GC/MS): Soot samples were washed with dichloromethane (DCM), obtaining a Soluble Organic Fraction (SOF) adsorbed on soot surface. These extracts were analyzed by GC/MS.
7) Soot reactivity with 2000 ppm of NO and 500 ppm of O_2 at 1000 ºC. Soot-NO interaction presents the benefit of reducing NO to N_2 (Arnal et al., 2012). Samples were heated in an inert atmosphere of N_2 up to the desired reaction temperature. In this way SOF is removed from the soot surface and only the carbonaceous core reacts with the reactant gases.

Soot tested come from fouling test in operation conditions point 1 (HC 200 ppm) and point 2 (HC 500 ppm) as identified in table 4.
Vehicle types of soot were chosen according with their appearance, from the most typical matt appearance (fig 11) to the varnished appearance shown in figure 12.

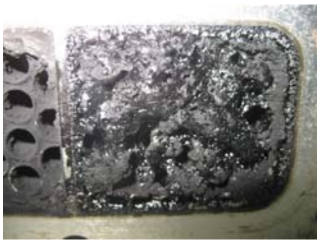

Fig 11 and 12 Types of soot: matt appearance (left) and varnish (right)

The test results show differences between the soot coming from fouling tests and vehicle summarized as follows. No noticeable difference was observed for parts coming from experimental fouling tests. That is the reason why the comparison establishes only comparison between these parts and vehicle parts. The objective is to analyze if chosen operation points in experiments can represent real operation conditions in vehicle.

- Elemental analysis shows higher H content in vehicle soots, indicating a higher presence of hydrogenated adsorbed molecules, probably partially burnt fuel. Carbon fractions are greater in fouling test what could suggest more graphitic structures.

- FTIR analysis indicates the presence of a great quantity of oxygenated functionalities and adsorbed hydrocarbons (aliphatic chains), where the last ones are mainly present in the vehicle soot and probably come from partially burnt fuel and/or lube oil.

- TGA in N_2 flow shows that soot coming from vehicle tests can double the percentage of mass losses (due to hydrocarbon desorption and decomposition of oxygenated functionalities) when compared to fouling soot coming from operating condition 2.

- TGA results in air flow show the same tendency that those found for N_2 flow up to ca. 350-400 ºC, because of hydrocarbon desorption and decomposition of oxygenated functionalities. Carbonaceous core starts to oxidize from this temperature on, showing lower combustion temperatures for vehicle soot than for fouling test soot.

- BET specific surface area of soot is smaller in vehicle soot than in fouling test soot, what may be due to the presence of a high quantity of adsorbed hydrocarbons and oxygenated functionalities, confirmed by FTIR.

- GC/MS analyses corroborate the presence of adsorbed hydrocarbons and a small quantity of light Polycyclic Aromatic Hydrocarbons (PAH). Most of the peaks correspond to aliphatic chains between C_{10}-C_{23}, while others indicate the presence of PAH between 2-4 rings.

- For both series of reactivity experiments, NO and O_2, matt soot resulted to be the most reactive soot (defining reactivity as the time needed for the complete carbon conversion, so the lower time the higher the reactivity) while varnished soot presented the lowest reactivity. The rest of the soot samples, including fouling soot, remained between these two vehicle samples. It is noteworthy to mention that matt soot achieved the highest NO reduction for a given carbon weight, however, varnished soot was the worse soot sample in reducing NO.

- Varnished soot (DS14) is characterized by the highest presence in HC and the lowest specific surface area.

CONCLUSIONS

1. Value of fouling resistance (R_f) is:
   Highly dependent on operation condition

  Slightly dependant on gas flow velocity (size)
  Not significantly dependant on EGR cooler technology

2. However, the degradation on EGR cooler function, that is, thermal efficiency is:
   Highly dependent on size
   Highly dependent on EGR cooler technology
3. Significant impact of operation condition. High HC content and high opacity have shown to be critical conditions.
4. Selection of best EGRC design depends on operation conditions.
5. Fouling obtained in controlled bench tests are not fully representative of vehicle conditions, so extreme effects as varnish can be present in parts recovered from vehicle tests.

NOMENCLATURE

Ac	Contact area
CO	Carbon monoxide
CO_2	Carbon dioxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
ECE	Elementary urban Cycle
EGR	Exhaust Gas Recirculation
EUDC	Extra Urban Driving Cycle
h	Convection heat transfer coefficient
HC	Hydrocarbon
HP	High Pressure
L	Length
LMTD	Logarithmic mean temperature difference
LNT	Lean NO_x Trap
NEDC	New European Driving Cycle
NO_x	Nitrogen oxides
PM	Particulate Matter
Rt	Overall thermal resistance
Rw	Wall resistance – conduction
S	Section
SCR	Selective Catalytic Reduction
U	Overall heat transfer coefficient

Subscript

c	contact
f	fouling
w	wall

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