

# Characterization of EGR Cooler Response for a Range of Engine Conditions

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## ABSTRACT

Fouling phenomenon is a key issue for EGR cooler operation. In spite of the fact that soot deposition is imposed by the characteristics of the exhaust gases flow, the design of the EGR cooler has a significant impact for effect on the engine. New combustion modes corresponding to new engine developments and combination of EGR system with other post-treatment devices make that fouling conditions for future generations of EGR coolers can be significantly different from previous applications from Euro 3 to Euro 5. An investigation has been performed in order to characterize the response of different EGR coolers designs for different conditions of the exhaust gases. As for the design, the technology selected has been tube-and-fin heat exchanger, which is a high performance technology that fits Euro 6 customer specifications. The variations in design have been made through modifications in fin characteristics, both in configuration and geometric dimensions. As for engine operation conditions, the exhaust gases characteristics have been modified from a standard calibration to get more severe fouling conditions, in terms of HC content, opacity, exhaust gas temperature and flow. The degradation of performance has been characterized through measurements of thermal efficiency and permeability. It can be concluded that HC content and opacity have a significant influence on fouling phenomena, and that EGR cooler optimum design is highly dependent on these exhaust gas conditions.

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## INTRODUCTION

Nowadays refrigerated EGR is a solution for NO<sub>x</sub> reduction that has been generalized following continuous tightening of environmental regulations. Customer requirements have imposed a roadmap for EGR coolers development that has resulted in a significant increase of thermal efficiency balanced with the permitted pressure drop for these heat exchangers. It has been achieved without a significant penalty on space. Thus, compact technologies for EGR coolers are being implemented in current and future engines.

Another challenge for EGR coolers is the requirement for durability of anti-pollutant devices. That is, function of the device must be maintained at a certain level after a period of use. In particular, for European emission standards, the verification condition for durability has been fixed in terms of a number of kilometers, varying from 80000 to 160000 km from Euro 3 to Euro5/6, or a number of years, in particular 5,

whichever occurs first [1]. However, there is no a clear criteria to define acceptance of the degradation, so application to EGR Cooler component design cannot be done. There are also specifications coming from some customers regarding fouling impact on the degradation of performance for the EGR cooler, both for thermal efficiency and pressure drop. The exposure conditions for that degradation are not always defined. In some cases, a given engine test is specified or a fouling factor is considered. In some others, degradation is not linked to any specification, and supplier experience is taken into account to evaluate performance change.

The specifications for fouling impact on EGR Coolers are much more generalized for Euro 6 applications than for previous engine generations. Two main concerns affect engine developers. On one hand, decrease in thermal efficiency and on the other hand increase in pressure drop. Decrease in thermal efficiency is directly linked to quantity of recirculated exhaust gas, since it means an increase in temperature and therefore a decrease in mass, so it affects to

NO<sub>x</sub> formation. Pressure drop increase can be assumed by EGR valve regulation up to certain level. However, if increase is very high it could compromise the position of air inlet valve, therefore decreasing engine performance.

EGR Cooler designer must have the knowledge to answer customer demands, anticipating to incidences that may occur during engine tuning. For that, characterization of EGR Coolers in engine with a wide range of operation conditions is needed. Past experiences are based on conventional combustion modes not representing possible use conditions of the heat exchanger for next generation of engines.

## Technology Tubes & Fins

EGR Coolers generations have evolved from typical “shell and tubes” technology with round smooth tubes to different shapes of these tubes to increase performance. Last generation of EGR Coolers include fins inside tubes in order to further enhance thermal efficiency [2]. Fins provide additional surface for heat exchange between exhaust gas and coolant in a given packaging. Fins are located at gas side where heat transfer resistance is higher thus limiting heat transfer in the heat exchanger.

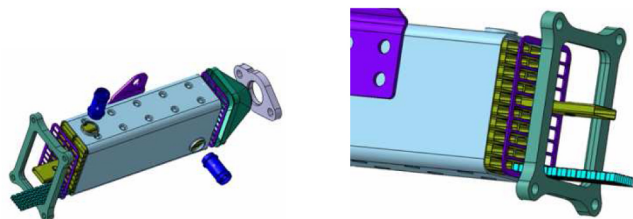


Figure 1. Tubes & fin technology in EGR Coolers

EGR coolers material for High Pressure EGR circuit is typically stainless steel. Feasible fins in this material are basically of two types: offset and wavy fins. Dimensional characteristics for the fin are: transversal pitch, height and longitudinal pitch. Quantity of additional surface provided by the fin is given by the transversal pitch and height. The lower these values are the higher heat transfer area is achieved. However it must be balanced with permeability, given the fact that a very dense fin means a high pressure drop for the EGR flow. As for longitudinal pitch, it provides turbulence for exhaust gas flow. Thus the lower longitudinal pitch the higher disorder of gas flow paths is obtained, increasing turbulence and therefore heat exchange. This strategy is also opposite to good permeability of the heat exchanger. In relation to the difference between offset and wavy fin, offset fin gives rise to higher disturbance of flow due to sudden flow direction change and enables better flow distribution because there is no separation between channels, that is, the different channels are connected due to the offset step. Wavy fin results in smoother gas flow paths following waves without connection between them.

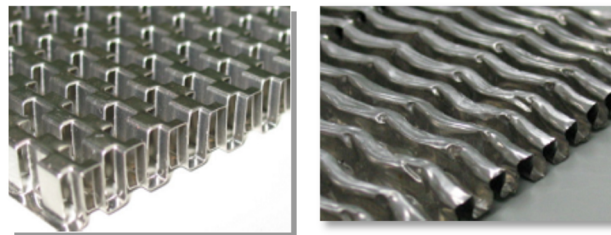


Figure 2. Fins types: offset (left) and wavy (right)

## Fouling in EGR Coolers

Exhaust gases coming from combustion in the engine causes deposition on internal surfaces of the EGR Coolers. This fouling layer decreases thermal efficiency due to its isolating nature, and also increases pressure drop due to reduction of section. The impact has been verified both in engine test benches and parts recovered from vehicles [3]

The fouling layer is mainly a mixture of soot and hydrocarbons, formed from deposition of exhaust gases that contain mainly CO, CO<sub>2</sub>, H<sub>2</sub>O, H<sub>2</sub>, CH<sub>4</sub>, un-burnt hydrocarbons, fine soot particles and nitrogenous compounds [4]. The physical mechanisms driving the creation of the fouling layer depend basically on the nature and size of particles in the gas flowing through the EGR cooler. The main mechanisms are thermophoresis and inertial impaction. The finest particles experience a force towards the cooler walls due to temperature gradient between the gas and the wall, much colder. These particles arrive at the surface with very low velocity and then stick to the wall. Thus, a thin layer is formed. Larger particles are then trapped by inertial impaction. The fouling layer has been reported to have asymptotic behavior for EGR Coolers after some time [5, 6].

The effect on EGR cooler performance is characterized by a fouling resistance factor that represents isolation. The fouling resistance is implemented in heat exchanger calculation as an additional thermal resistance for heat flux. Given the heat transfer from the following equation, where total thermal resistance is the inverse of overall heat transfer coefficient (UA),

$$Q = U \cdot A \cdot \Delta T_{ml}, \text{ with } R_t = \frac{1}{U \cdot A}$$

the fouling thermal resistance is summing up to gas side convection, conduction through the wall and coolant side convection.

$$R_t = \frac{1}{h_{gas} \cdot A_{c_{gas}}} + R_w + \frac{1}{h_{coolant} \cdot A_{c_{coolant}}} + \frac{R_f}{A_{c_{gas}}}$$

In this latter equation, thermal resistance in gas and coolant side is given by convection coefficient (h), and R<sub>w</sub> represents conduction resistance. Fouling resistance is represented by R<sub>f</sub>, and it must be noticed that the influence of this value on the overall resistance is divided by contact heat

transfer area. A simple evaluation of magnitude for the different thermal resistance results that the most important terms are gas side resistance and fouling. In the case of fouling resistance, the effect is minimized if heat transfer area is increased. Thus, tubes and fins technology has a lower impact with same value of  $R_f$  that is given by engine operation conditions. In previous work, it has been verified that the fouling resistance is not dependent on the heat exchanger technology. However, the impact on thermal efficiency is very dependent: technologies with higher heat transfer surface are less sensible to fouling effect. Value of the thermal resistance for standard engine operation conditions can vary from 0.002 to 0.005 m<sup>2</sup>.K/W [7].

## CHARACTERIZATION OF EGR COOLER RESPONSE

### Experimental Facility

In order to perform the tests campaign, automotive 2.0 liters turbocharged diesel engine has been used. The engine fulfills Euro 4 regulation. This engine has been installed into a test bench, coupled to a dynamometer in order to control torque and speed. Pressure and temperature transducers have been placed at the intake and exhaust manifolds. A particular instrumentation has been used in order to characterize the EGR cooler fouling. Temperature and pressure checking points have been carefully selected in order to properly obtain EGR cooler drop pressure and efficiency. Air mass flow has been registered using a hot wire flow meter.

The engine has an open code ECU that allows tuning the engine calibration to control automatically the valves position and injection set points, from signals such as those provided by the air mass flow and intake pressure sensors. Since the EGR cooler performances change during the test, some calibration parameters need to be modified in order to keep the EGR gas conditions and exhaust pollutant concentrations.

A Horiba Mexa 7100 DEGR has been used to measure the intake CO<sub>2</sub> concentration and exhaust gas emissions (NO<sub>x</sub>, HC, CO, CO<sub>2</sub> and O<sub>2</sub>). Both intake and exhaust CO<sub>2</sub> have been measured by a non-dispersive infrared analyzer (NDIR). NO<sub>x</sub> are measured by means of a heated chemiluminiscent detector (HCLD). The HC analyzer is a heated flame ionization detector (HFID). In the same way, an AVL 415s Bosch-type smoke meter has been used to measure smoke opacity.

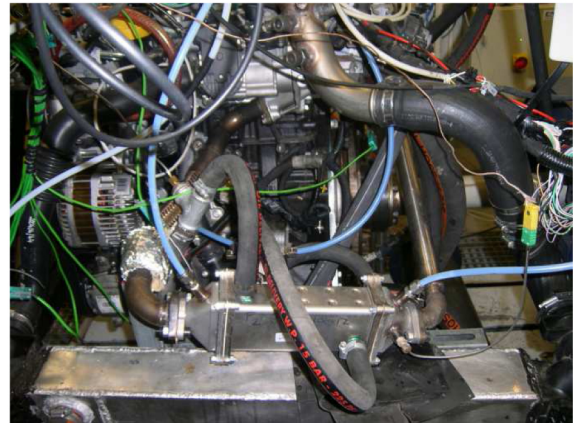


Figure 2. EGR Cooler implemented in engine bench

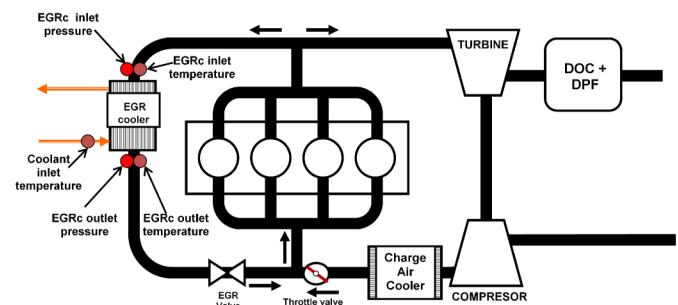


Figure 3. Sketch of EGR Cooler implementation

### Test Definition

The main objective of the tests is to compare different design alternatives for tube and fin technology with different engine operation points. It does not intend to be representative of real performance on the engine but to be used as a basis to discriminate between different designs of EGR coolers.

Selection of the operation conditions of the engine has been based on exhaust gas temperature, flow and composition. These are the parameters with a higher influence on fouling layer formation [8]. The operation points represent new applications for Euro 6 engines, where new combustion modes appear and the EGR area is widened. Also the combination of EGR system with other anti-pollutant devices, such as Selective Catalytic Reduction (SCR) or deNO<sub>x</sub> catalyst, can impose new conditions for EGR Cooler.

Baseline operation conditions are in the range of following parameters: exhaust gas temperature 300 - 500°C, gas flow 5-20 g/s, HC content 20-60 ppm, smoke opacity 1-2 FSN. For comparison a standard calibration point has been selected with following parameters: 420°C, 13 g/s, 60 ppm HC and smoke opacity 2 FSN. In the engine used, these conditions are achieved without any modification. Other four points have been defined for the test. They are representative of: high HC content, critical HC content, high smoke opacity and high gas flow. Modifications in engine operation