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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.

INTRODUCTION

Nowadays refrigerated EGR is a solution for NO_x 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 will affect to NOx 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.

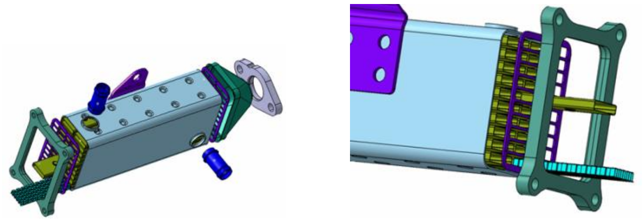

Figure 1: Tubes & fin technology in EGR Coolers

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 would mean 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 of communication between channels. Wavy fin results in smoother gas flow paths following waves without communication.

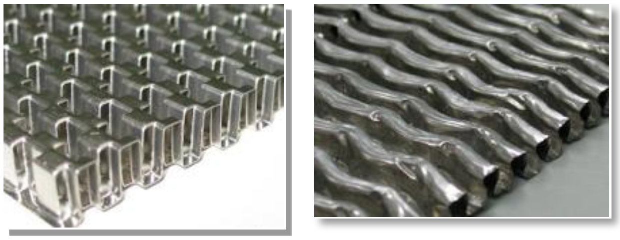

Figure 2: Fins types: offset (left) and wavy (right)

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_2, H_20, H_2, CH_4, 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 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_w represents conduction resistance. Fouling resistance is represented by R_f, 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 will be minimized if heat transfer area is increased. Thus, tubes and fins technology will have a lower impact with same value of R_f that will be given by engine operation conditions. In previous work, it has been verified that the fouling resistance is not dependant on the heat exchanger technology. However, the impact on thermal efficiency is very dependant: 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^2.K/W [7].

CHARACTERIZATION OF EGR COOLER RESPONSE

Experimental facility

CMT

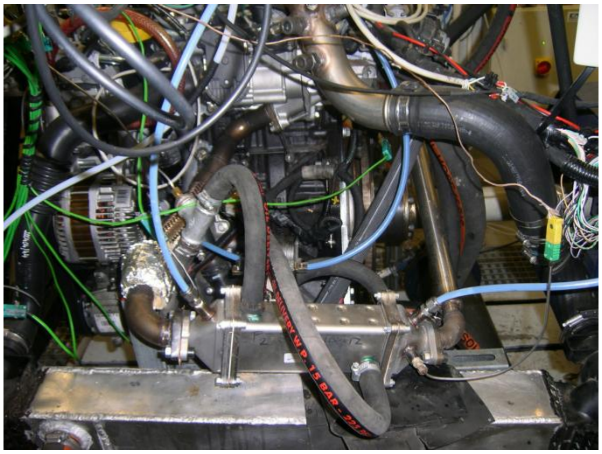

Figure 2: EGR Cooler implemented in engine bench

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.

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 deNOx catalyst, can impose new conditions for EGR Cooler.

Baseline operation conditions are in the range of following parameters: exhaust gas temperature 300 – 500ºC, 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: 420ºC, 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 parameters have been done, especially related to injection and valve timing. Thus, five engine operation points are defined.

Table 1. Test operation points.

	HC (ppm)	Opacity (FSN)	T gas (ºC)	Q gas (g/s)
Standard calibration	60	2	420	13
Operation point 1	200	1.8	450	13
Operation point 2	500	2.2	500	13
Operation point 3	200	3.1	510	14.5
Operation point 4	200	2.7	450	16.5

A summary of definition of points is listed below:

- Operation point 1: similar to standard calibration but with a high HC content (200 ppm).
- Operation point 2: significant change of HC in relation to operation point 1. This is the highest peak that could be expected for EGR Cooler operation (500 ppm). Engine regulation imposes higher opacity and higher gas temperature.
- Operation point 3: maximum opacity (3,1 FSN) combined with high HC content (200 ppm). Increase of temperature and gas flow due to engine regulation.
- Operation point 4: maximum gas flow achievable with the engine (16.5 g/s) with high HC content (200 ppm). Opacity also results in a higher value than standard calibration.

Regarding designs of the EGR cooler, same external packaging has been considered. It has been taken a reference heat exchanger core space of 180 mm length, 51 mm width and 77 mm height. Technology for the EGR cooler is tube and fin, with offset and wavy fins inside the tube. Five different alternatives of fins were selected. The table below shows a summary with the more relevant geometrical characteristics.

Table 2. Fin parameters

	Type	Height (mm)	Transversal pitch (mm)	Longitudinal pitch (mm)
Fin A	Offset	5	4.2	6.3
Fin B	Offset	5	5.2	3.1
Fin C	Offset	5	6.9	3.1
Fin D	Wavy	5	4.4	9.5

Fin E	Wavy	5	8	9.5

A total of sixteen tests have been performed with the following combination of engine operation conditions and fin designs:

- Standard calibration: Fin A / D
- Operation point 1: Fin A / B / C / D / E.
- Operation point 2: Fin A / B / C / D / E.
- Operation point 3: Fin A / E.
- Operation point 4: Fin A / D.

As it is intended for comparative analysis, 8 hours of tests have been done, without stopping of the engine.

Initial characterization of parts

Characterization of EGR coolers is first made in a test bench where hot clean air flow through the heat exchanger. Basic value for performance is taken from this test, since this is the one that corresponds to thermal calculation for heat exchange, without taking into account implementation in the engine. In this test bench both thermal efficiency and gas pressure drop are measured.

If reference is taken for offset fin of transversal pitch 4,2 mm and longitudinal pitch 6,3 mm, performance at 25 g/s are as follows:

Table 3. Thermal efficiency at clean status

Fin type / t. pitch / l. pitch	Thermal efficiency
Offset / 4,2 / 6,3	Baseline
Offset / 5,2 / 3,1	+2%
Offset / 6,9 / 3,1	-4%
Wavy / 4,4 / 9,5	≈
Wavy / 8 / 9,5	-10%

Table 4. Gas pressure drop at clean status

Fin type / t. pitch / l. pitch	Gas pressure drop
Offset / 4,2 / 6,3	Baseline
Offset / 5,2 / 3,1	+13%
Offset / 6,9 / 3,1	≈
Wavy / 4,4 / 9,5	-13%
Wavy / 8 / 9,5	-20%

Results and discussion

Results are evaluated from engine tests each half an hour. Thermal efficiency and gas pressure drop are calculated from measurements of thermocouples and pressure transducers:

$$Efficiency\ : \quad \varepsilon = \frac{\left(T_{gas,inlet} - T_{gas,outlet}\right)}{\left(T_{gas,inlet} - T_{coolant,inlet}\right)}$$

$$\Delta p \quad = P_{gas,inlet} - P_{gas,outlet}$$

In order to understand the impact of the different operation conditions, first comparison is established for fin A which is tested for all engine points.

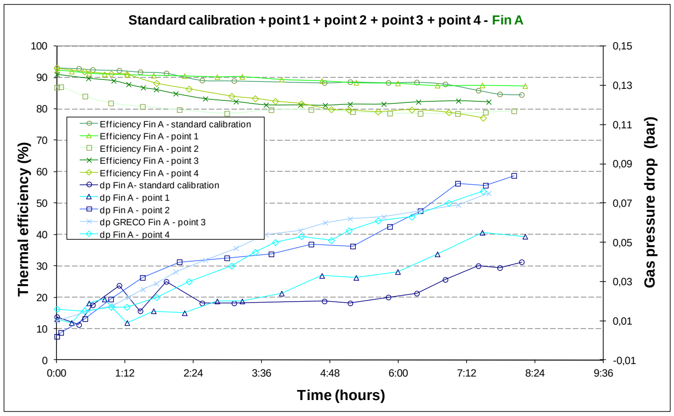

Figure 3: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin A / all operation conditions

As it can be seen from the graph above, the effect on gas pressure drop is especially significant for conditions 2, 3 and 4 (highest HC, high HC & high opacity, high HC and high gas flow). The value measured is bigger than 4 times gas pressure drop for standard calibration. The operation condition 1, with high HC (200 ppm), results in a more moderate impact in this value.

The critical effect of conditions 2, 3 and 4 can also be noticed in thermal efficiency. Values after 8 hours of test attain a level around 80% meanwhile standard calibration and operation condition 1 shows a value around 86%. Calculation of fouling resistance for these conditions gives values varying from 0.007 to 0.009 m^2.K/W for conditions 2, 3 and 4, and values from 0.005 to 0.006 m^2.K/W for standard calibration and operation condition 1.

CMT: Operation of valves: EGR and air throttle

If a similar comparison is established for a type of fin with similar thermal efficiency, fin D can be selected to understand impact of wavy design in relation to offset. For this type of fin, operation point 3 has not been run. As for wavy fins, there is previous literature establishing differences with offset fins but only for a given operation condition [9].

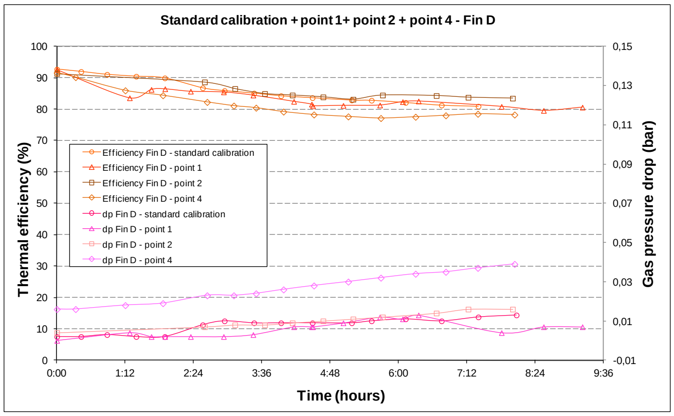

Figure 4: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin D / conditions: standard, point 1, point 2 and point 4

The most remarkable result is that there is a significant difference of the behavior regarding gas pressure drop increase in relation to offset fin. This increase is much lower for wavy fin for all operation conditions. Condition number 4 shows a higher impact linked to the higher gas flow (16.5 g/s in relation to 13 g/s). As for thermal efficiency, calculation of fouling resistance results in similar values for conditions 2, 3 and 4. However, fouling resistance is higher for this type of fin for standard calibration and condition 1. A value of 0.008 m^2.K/W is obtained in relation to values from 0.005 to 0.006 m^2.K/W for offset fin.

As a conclusion, it can be stated that a meaningful difference appears for these types of fins depending on the operation conditions. If only standard calibration and operation condition 2 (one of the most critical with HC content 500 ppm) are taken, difference is clearly exposed in figures 5 and 6. Whereas offset fin shows better thermal efficiency with a slight penalty in permeability for standard calibration, the results changes significantly with operation condition 2. In this condition, wavy fin shows better thermal efficiency with is balanced with a significant lower gas pressure drop.

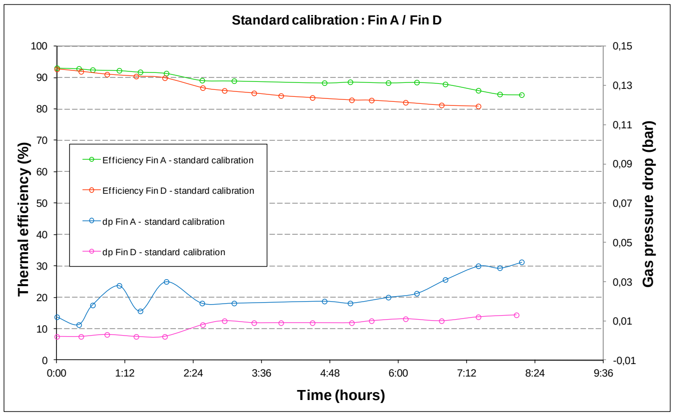

Figure 5: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin A & D / standard calibration

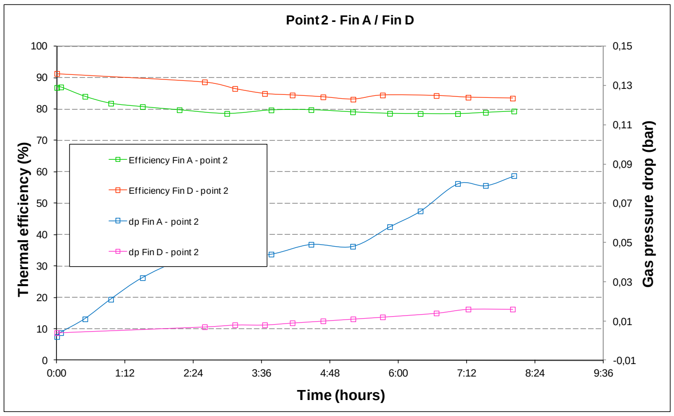

Figure 6: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin A & D / point 2

If an observation is done for type of fouling that appears for standard calibration and operation condition 2, it is clear that the soot layer is thicker in the latter condition. In this condition it can be also observed that extreme gas tubes, where gas flow repartition is lower, show a higher fouling with a fluffy aspect. On the contrary, fouling in standard calibration do not show differences between tubes and soot appears like a thin layer attached to the tube and fin surfaces.

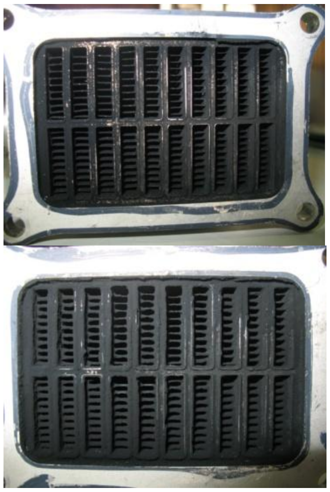

Figure 7: Soot layer in standard calibration (left) and operation condition 2 (right)

So far two fins have been used where heat transfer surface is similar, given the fact that they have similar fin transversal pitch. That is why they show similar thermal performance in clean status. The difference in longitudinal pattern, offset and wavy, makes the difference for gas pressure drop in clean status and also determines different fouling deposition that depends much on engine conditions.

As for these types of fins, wavy and offset, there are alternatives to vary fin parameters. The drivers for these modifications are:

- Increase of transversal pitch to get lower gas pressure drop without a significant penalty on thermal efficiency.

- Decrease of longitudinal pitch in offset fin to get more turbulence in gas flow so fouling deposition could be decreased.

As for wavy fin, alternative to fin D is fin E where transversal pitch is increased from 4.4 to 8 mm without a variation in longitudinal pitch.

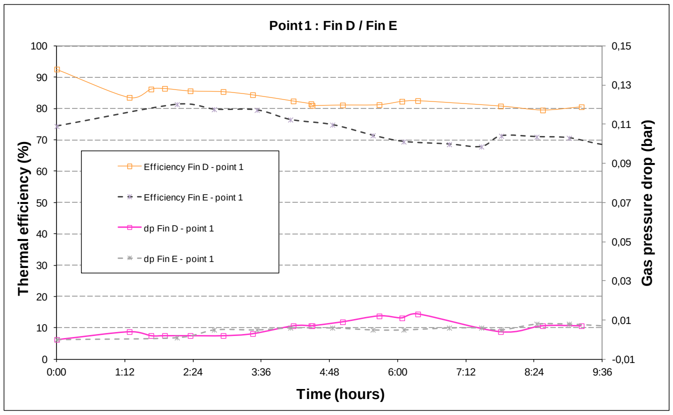

Figure 8: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin D & E / point 1

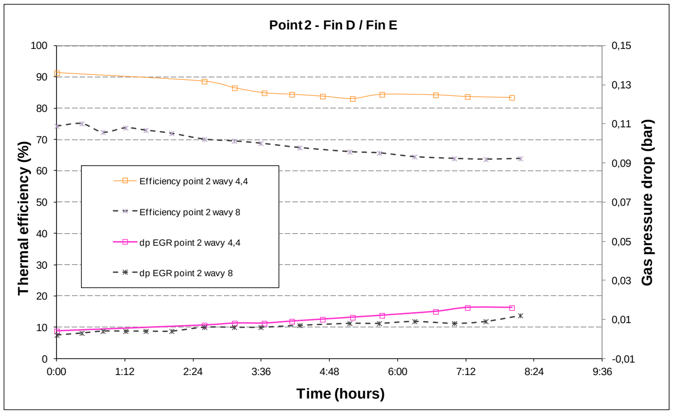

Figure 9: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin D & E / point 2

As for offset fin, alternative to fin A is the increasing of transversal pitch from 4.2 to 5.2 and 6.9 mm with a decrease of the longitudinal pitch from 6.3 to 3.1 mm.

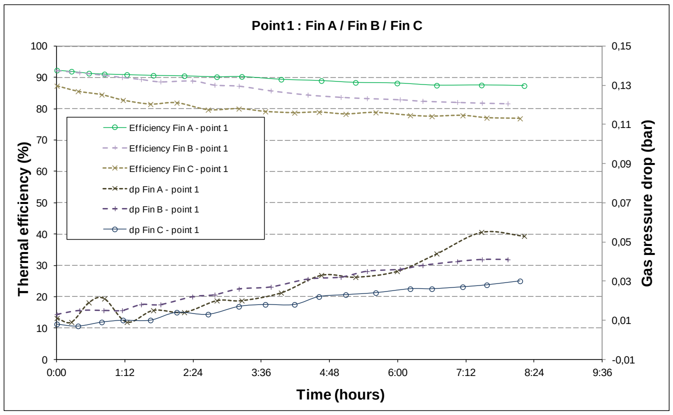

Figure 10: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin A, B & C / point 1

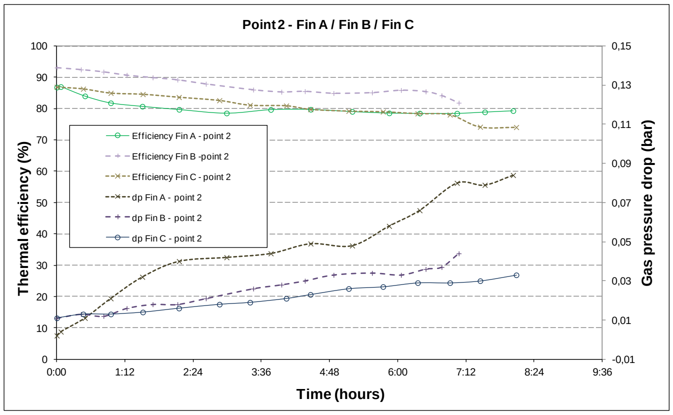

Figure 11: Thermal efficiency and gas pressure drop evolution for 8 hour-test: design Fin A, B & C / point 2

SUMMARY/CONCLUSIONS

- Significant impact of operation condition. High HC content and high opacity have shown to be critical conditions.
- Selection of best EGRC design depends on operation conditions.
- GRECO standard shows the best behaviour in thermal efficiency for standard conditions.
- GRECO standard shows a significant increase in gas pressure drop for critical conditions.
- If a low pressure drop is required wavy fin must be applied
- Communication with customer is crucial to minimise fouling effect on engine

Validation of EGR cooler design must be made in an engine test bench. It enables to foresee what customers will experience at EGR cooler validation.Measurements at performance test bench do not show how performance at test will evolve in time. As an example, a difference of only 10% in gas pressure drop at clean status can evolve to a difference of 300% at the engine. This is very important since permeability of the EGR cooler will affect engine operation through EGR valve and throttle actuation. A very high increase in gas pressure drop can result in a throttle actuation that can give rise to a penalty in engine performance through reduction of intake air.Impact on thermal efficiency is more predictable through evaluation of fouling thermal resistance. It is considered that fouling resistance does not depend on heat exchanger design but on engine operation condition, since it represent the isolation for thermal exchange. In this project, variations with the same engine operation point have been found ranging from 0.006 to 0.009. But taking into account that these variation comes from a variation in thermal efficiency of 5%, it is inside range of variability for measurements, especially when engine measurements are considered.

Further research in this field is needed in order to:

- Reach stabilization of measurements in order to reach asymptotic behavior of fouling phenomena (if possible).
- Definition of a test procedure trying to be representative of vehicle conditions (cyclic conditions).

- Exposure of different technologies at different operation points to understand different phenomena in the fouling deposition.

- Characterization through fouling thermal resistance (as done currently) and through decrease in gas pressure drop by correlation of fouling layer measurement.

- Implementation of different engine configurations:
    - Low temperature coolant circuit
    - Low pressure EGR circuit
    - Gasoline engines

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DEFINITIONS/ABBREVIATIONS

EGR	Exhaust Gas Recirculation
SCR	Selective Catalytic Reduction
FSN	Filter Smoke Number