ABSTRACT

Emission legislation for Off Road Engines is forcing the industry to review the engine design, introducing state of the art technology for many components and tailored exhaust gas after treatment architectures. Particulate matter reduction is a crucial issue to be addressed having an influence on overall engine performance and cost. At the present stage there is not a unilateral solution in the industry, as some manufacturers use a combination of very high fuel injection pressure and very efficient DOC, while others rely on the automotive derived DPF technology with active regeneration or SCR-only technology to reach EU Stage IV and US Tier4f. Considering the pros and cons of each solution, VM Motori decided to adopt an innovative solution consisting in a DOC followed by a partial-flow filter PM-Metalit® for the R750 Engine family. The advantages of this solution will be discussed in this paper along with the application work that has been carried over to reach the emission limit. A short overview of the PM-Metalit technology will be given together with a comprehensive explanation of the physical mechanisms that allow a constant and maintenance-free PM reduction. Moreover, tests results to simulate real life conditions will be discussed.

INTRODUCTION

In response to increasingly stricter emissions legislation, exhaust gas after treatment systems have been used as original equipment in off road engines since 2011, starting with engine with power between 130 and 560 kW down to lower power range. Applications within the range between 37 and 56 kW will have to meet the EU Stage 3B and US Tier 4 Interim within 2013 (Figure 1), keeping this exhaust system layout at least until future EU Stage 5 or US Tier 5 will be released.

The introduction of the lower emission limits and, at the same time, the new non-road transient cycle (Figure 2) with a cold and a warm cycle will lead to much more complex development of new engines taking also into consideration the influence on overall performance and costs of the exhaust gas after treatment.

Figure 1: An overview of worldwide non-road emissions legislation

The non-road transient test cycle (NRTC, Figure 2) includes a sequence of load collectives of various non-road applications, such as backhoes, wheel loaders, bulldozers, agricultural vehicles, power shovels and skid loaders.

Regardless of their later application, engine emissions will be tested based on standardized test cycles, which will raise requirements to emission after treatment effort accordingly.

The wide variety of applications with often small production batches demands efficient system planning and design. A modular design or a building-block system using standardised components is more suited to this scenario avoiding an unacceptable increase in application-specific engineering costs.
Increasingly indicates that the overall solution from an economic point of view is the best way to reduce emissions while ensuring customer satisfaction. Each parameter is necessary, using for example external efficiency, impact on fuel economy, cost, space and technical point of view, for example, efficiency, impact on fuel economy, cost, space requirements and impact on vehicle design. Each parameter has been evaluated by means of a weighting factor leading to an overall ranking level.

For example, PM Metalit is maintenance free, this has a positive influence on the overall ranking comparing the PM Metalit, the DOC only system with a DPF system. On the other hand, the DOC only approach is not so cost effective as the DOC + PM Metalit solution, considering the overall engine cost related to each component.

The final result of this evaluation process clearly indicates the combination of DOC plus partial-flow deep-bed filter (PM-Metalit) as the more suitable exhaust gas after treatment system for the R750IE4 engine family.

**PM-METALIT: PARTIAL FLOW DEEP BED FILTER**

Emitec’s PM-Metalit partial-flow deep-bed filter (Figure 3) has been successfully used in commercial vehicles and passenger cars since 2004. The PM-METALIT is the only mass-produced first equipment filter system in the world that has been designed for the entire service life of the engine without requiring further maintenance.

This approach would lead to the implementation of overall systems consisting of vehicle, engine and exhaust after treatment that represent an optimum solution from an economic and technical point of view.

Basically, two different approaches are available to comply with EU Stage 3B and US Tier 4 Final: either to improve the engine combustion to a level that no PM (Particulate Matter) after treatment is necessary, using for example external cooled EGR and high pressure common rail, or to use a more standard engine technology and rely on a very efficient PM reduction, for example with a DPF (Diesel Particulate Filter).

VM Motorex used a different and innovative approach carrying out an evaluation process in which the different technologies (regarding engine and after treatment) have been compared from different points of view, for example, efficiency, impact on fuel economy, cost, space and technical point of view.

![Figure 2: Non-road transient test cycle (NRTC) with application-related load collectives](image)

**AVAILABLE TECHNOLOGIES**

Global warming is one of the most discussed topics and it is generally related to the CO₂ concentration in the atmosphere: in addition to soot, methane, nitrogen oxides, etc. it is the effect of CO₂ that has become a matter of public concern. Governments regard the CO₂ released through human activity, primarily as the product of combustion processes, as the main cause of climate change. Moreover, as far as internal combustion engines are concerned, CO₂ emissions equal fuel consumption and hence operating costs.

The resulting conflict of objectives primarily affects engine development because efficient exhaust after treatment tends to increase fuel consumption. Consequently, increasingly stricter emission limits on harmful pollutants can be expected to have a negative impact on future fuel savings or CO₂ reduction potential. The selection of the proper catalyst and filter system therefore becomes crucially important because the technical design is closely linked to the balance between customer and environmental benefit. Vehicles with this double competitive advantage and a simple, durable exhaust after treatment system are going to succeed in the market.

This approach would lead to the implementation of overall systems consisting of vehicle, engine and exhaust after treatment that represent an optimum solution from an economic and technical point of view.

![Figure 3: PM-Metalit; partial-flow deep-bed filter for particle reduction of light- and heavy duty engines](image)
accumulation. Therefore it can be installed in relatively cold applications, which would have major regeneration problems in case of traditional wall flow Particulate Traps.

Furthermore flow through devices, such as the PM-Metalit, are not sensitive to ash accumulation issues.

**R750IE4 FAMILY ENGINES**

The R750IE4 engine family has been recently revised to comply with EU Stage 3b and US Tier4i emission legislation. The version with engine power below 56kW are equipped with common rail, internal EGR, turbo with intercooler, DOC and PM Metalit exhaust after treatment. Technical features are reported in the table 1.

<table>
<thead>
<tr>
<th>Bore x Stroke</th>
<th>94 x 107 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>3 or 4</td>
</tr>
<tr>
<td>Valve</td>
<td>2</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.8 : 1</td>
</tr>
<tr>
<td>Injection Type</td>
<td>Direct</td>
</tr>
<tr>
<td>Intake</td>
<td>Turbocharged</td>
</tr>
<tr>
<td>Cooling</td>
<td>Liquid cooled</td>
</tr>
</tbody>
</table>

Table 1: Technical features of the R750IE4 engine family

Figure 4 shows the Power and Torque characteristic of the engine in the 50 kW version while Figure 5 shows the smoke engine out emission.

Figure 6 shows the engine lay out, in this case in the 3 cylinder version. As it can be observed, a Lambda sensor in front of the DOC is present along with 2 temperature sensors, the first in front of the DOC and the second between DOC and PM Metalit. Table 2 shows the technical features of the engine family.

**AFTER TREATMENT LAY-OUT DESCRIPTION**

A modular approach has been used to design the exhaust gas after treatment. DOC and PM Metalit are integrated in one canning together with 2 temperature sensors. Different inlet and outlet cones can be used to better match the engine compartment space constraint.
In any case, some general parameters such as inlet temperature and flow distribution, are considered in detail for each application.

The PM Metalit has a diameter of 118mm and a length of 174mm. The total volume is about 1.9 liter allowing a very compact system, as it can be observed in Figure 7.

The diameter has been chosen to ensure that the backpressure is below the engineering limit, in order to have a limited impact on performances and fuel consumption, and that the channel flow velocity is high enough to reach the desired overall conversion efficiency.

The presence of the 2 temperature sensors can be used also to detect the presence of the after treatment (anti-tampering strategy).

**APPLICATION OF THE PM-METALIT**

Engine calibration has been designed to reach a NMHC + NOx engine out as close as possible to 4 g/kWh. The resulting engine out particulate emission is 59 mg/kWh while the engine target for European and US legislation has been set to 20 mg/kWh. A total particulate conversion efficiency of about 65% is requested.

Figure 8 shows the US and EU legal limits, the engineering target and the emission results with US and EU standard fuel during the Non Road Steady Cycle (NRSC) and Non Road Transient Cycle (NRTC) used for engine homologation.

A deterioration factor test has been started with a target of 4,000 hrs.

Table 2 shows the load factors used during mileage accumulation test. The high speed / high load operating condition represent the 75% of the entire test, this simulate a very heavy average load during entire engine life, it can be assumed that during real life the mean engine load will be much lower.

**Table 2: Mileage accumulation test operating conditions**

<table>
<thead>
<tr>
<th>engine operation condition</th>
<th>share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>10</td>
</tr>
<tr>
<td>Low Speed / Medium Load</td>
<td>5</td>
</tr>
<tr>
<td>Transient</td>
<td>10</td>
</tr>
<tr>
<td>High Speed / High Load</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 9 shows the NRTC emission test results at different mileage accumulation intervals. The tailpipe particulate mass remains more or less constant, confirming the low sensitivity of the system with respect to the aging and ash accumulation.

**REGENERATION STRATEGY**

As stated in a previous chapter, the PM Metalit is designed to be regenerated mainly by passive regeneration which works continuously without any further controls as long as a given set of boundary conditions (e.g. temperature, mass
flow, oxidizing agents like O$_2$ or NO,$_2$ is maintained (Figure 10).

![Figure 10: Schematic representation of the continuous regeneration](image)

The presence of NO,$_2$ is essential to ensure the particulate oxidation (eq 1 and 2):

1) C(Soot) + NO$_2$ $\rightarrow$ NO + CO
2) C(Soot) + 2NO$_2$ $\rightarrow$ 2NO + CO$_2$

The NO$_2$ engine out emission are usually low and being NO$_2$ a very strong oxidizing gas, it reacts with HC and CO before HC and CO are well converted in the DOC (Figure 11 and [4]).

![Figure 11: NO$_2$ consumption and formation vs. exhaust gas temperature](image)

For this reason the presence of a very efficient DOC is necessary to oxidize NO to NO$_2$ and ensure the passive regeneration. Otherwise, in the presence of HC and CO, engine-born or catalytically generated NO$_2$ will oxidize these species under low temperature conditions as shown in Figure 11, resulting in low amounts of NO$_2$ downstream the oxidation catalyst and a shift to higher temperatures for the release of NO$_2$ behind the oxidation catalyst. Various manufacturers of catalytic coatings report that about 80% of the hydrocarbons have to be converted before the formation of NO$_2$ over the DOC starts.

![Figure 12: NO$_2$ formation and dissociation vs. exhaust gas temperature](image)

In order to ensure a reliable passive regeneration operation, NO$_2$ concentration should be as high as possible. There is no upper limit, but NO$_2$ can only be utilized if temperature is sufficient. On the other hand, NO$_2$ is a greenhouse gas and there is an increasing tendency in several countries around the world to monitor or even cap the acceptable emitted amount in traffic. So, a well-balanced oxidation catalyst is mandatory for a good operating passive regeneration system.

At temperatures above 500°C, depending on the oxygen concentration in the exhaust gas and on the nature of the tested soot, regeneration with oxygen has to be considered as an alternative mechanism. This reaction is more exothermic ($\Delta G_{298} = -394.4$ kJ/mol for oxygen vs. $\Delta G_{298} = -321.8$ for NO$_2$) and has a much faster reaction rate.

Fuel quality plays also a key role, considering that in presence of SO$_2$, the formation of NO$_2$ is reduced due to competitive adsorption processes between SO$_2$ and NO$_2$ and a reversible deactivation of the catalyst occurs. The oxidized SO$_2$ tends to react with the washcoat as sulfate-formation. This increases the light-off temperature for NO$_2$ formation. A by-product of the oxidation of SO$_2$ is the formation of sulfates (resp. sulfuric acid), which passes the PM-Metalit® in the gas-phase and condenses in the analytical filter of the gravimetric PM analyser, leading to increased PM-emissions over the test.

Another important parameter is the exhaust gas temperature: NO$_2$ can be oxidized from NO and O$_2$ starting at about 180 – 200 °C. This mechanism is represented by the dotted line (Figure 12) in the temperature range up to ~250 °C. At the same time NO$_2$ is thermodynamically controlled at temperature above ~250°C. This is represented in Figure 12 by the continuous line showing that at increasing temperatures NO$_2$ (left y-axis) dissociates in NO (right y-axis). Consequently only a limited temperature window is useful for the operation of a DOC to produce NO$_2$ out of NO needed for a proper passive regeneration of the PM Metalit, as represented by the green area in Figure 12.

The amount of NO$_2$ built under operating conditions depends on the exhaust gas temperature, space velocity of the DOC and the engine-out emissions of HC, CO, NOx, SO$_2$ and PM.

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compared to regeneration with NO$_2$. This leads to a higher temperature of the exhaust gas and the metallic structure for the same conditions of exhaust mass flow and PM-Metalit loading status. Critical in this respect is the self-acceleration of the reaction due to increasing temperature of the oxidizing soot, where only oxygen transfer to the reaction zone is limiting the reaction rate. In NO$_2$ regeneration this self-accelerating reaction is suppressed by the thermodynamic instability of the NO$_2$ under high temperatures.

Consequently oxygen regeneration requires an accurate process control and a good estimation of the stored soot in order to prevent any risk of exceeded temperature.

If the PM Metalit works under well balanced condition and the passive regeneration effect is ensured, the filtration efficiency will remain constant during life time. On the contrary, if the PM Metalit works under un-balanced conditions, the soot loading will increase, along with the backpressure, while the particulate conversion efficiency will decrease. The result is a deterioration of the engine performance due to increased backpressure and an increased particulate tailpipe emission.

It is clear that the regeneration strategy plays a crucial role to ensure a durable and efficient particulate filtration.

Figure 13 shows the temperature at DOC inlet over the engine map, it can be observed that the temperature values allow the continuous regeneration for most of the loading points.

**Figure 13: Temperature at exhaust gas after treatment inlet**

Figure 14 shows the engine out NOx over PM mass ratio. It can be observed that the NOx over PM ratio is particularly favorable for the passive regeneration operation.

**Figure 14: Engine out NOx / PM mass ratio**

It is possible to carry out some preventive analysis to ensure that during real life the operating temperature will be most of the time within the appropriate range. On the other hand, it is almost impossible to prevent the operator to run the engine, for example, on idling for a long time. In this case the passive regeneration operation could not be ensured.

To prevent any excessive soot accumulation on the PM Metalit, which could negatively affect the efficiency, it is necessary to implement a forced regeneration strategy. The frequency of this forced regeneration should be a compromise between soot accumulation during low temperature run and the related increase of fuel consumption. A detailed analysis, taking into consideration the soot emission during low load run and related accumulation in the PM Metalit, allowed VM Motori to find the frequency of regeneration that can prevent in any case excessive soot accumulation with a minimum impact on fuel consumption.

The final regeneration strategy consists of 3 steps:

1. Continuous regeneration. A soot model will estimate the actual soot loading in the PM Metalit.
2. In case the allowed limit will be exceeded a forced regeneration will start.
3. In any case, a forced regeneration will be started after 25 hours of engine run.

Engine derating strategy and Malfunction Indicator Lamp (MIL) warning will be also used.

**ASH ACCUMULATION**

Ash emitted from the engine as consequence of fuel combustion or lubricant consumption can be partially collected in the PM Metalit.

The first and more evident consequence of the ash accumulation is the increase in backpressure.
Figure 15 shows the increase of backpressure due to ash loading of the PM Metalit after 1400, 2000 and 4000 hours of mileage accumulation test with forced regeneration at a given interval.

**Figure 15**: Increase of backpressure due to ash accumulation during mileage accumulation test

It can be observed that the backpressure increase tends to have an asymptotic value, it is in any case important that the increase in backpressure has no negative influence on particulate tailpipe emission and engine performances (Figure 9).

**SUMMARY/CONCLUSIONS**

For the new R750IE4 VM Motori engine family a dedicated exhaust gas after treatment has been developed, consisting in a DOC and PM Metalit, for power range below 56kW.

Using this after treatment system, it is possible to reach EU Stage 3b and US Tier4i.

The extremely compact exhaust after treatment system allows the installation in close coupled position under the hood or in the engine compartment.

The particular internal architecture of the PM Metalit allows maintenance free service for life.

A dedicated regeneration strategy has been implemented in order to guarantee a constant particulate tailpipe emission value during the entire engine life preventing any un-desired excessive soot accumulation.

Ash accumulation test shows an increase in backpressure of the exhaust system with no negative influence on engine performances or particulate tailpipe emissions.

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**NOMENCLATURE**

DOC Diesel Oxidation Catalyst  
DPF Diesel Particulate Filter  
SCR Selective Catalyst Reduction  
NRTC Non Road Transient Cycle  
NRSC Non Road Steady State Cycle  
EGR Exhaust Gas Recirculation

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