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Innovative 2 Wheeler Substrate Developments for EU5

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ABSTRACT

Future tighter emission limits for 2 wheelers in Europe and worldwide will require a completely new approach in catalyst system design. In particular, the EU5 scenario, probably with the same emission limits as 4 wheelers and, for the first time, emission durability requirements, needs a new strategy to combine higher and durable conversion efficiency with the classical characteristics of 2 wheeler systems: low cost, low weight with minimum impact on exhaust system lay-out and engine out performances such as low fuel consumption and good power output.

This paper deals with the investigation of innovative metallic substrates keeping constant, as a first step towards the development of an EU5 system, both washcoat technology and PGM loading. In particular the effect of turbulent structures in the substrate, using PE (Perforated Foils) and LS (Longitudinal Structure) have been thoroughly investigated in testing 400cpsi PE and LS substrates.

After a brief review of past experiences with structured foils, a first test matrix was designed with the catalysts tested at constant engine load point to prevent any influence of test set up, engine characteristics and temperature profile. The three best performing substrates have been tested again using the roller bench and WMTC Cycle to compare them with the production system in order to highlight the relative efficiency improvement. An EU3 production motorbike with state of the art engine and lambda-sensor has been chosen to carry out the test.

The result of this investigation proves that high cell density metallic substrates with turbulent structures improve dramatically the conversion efficiency of the catalytic converter and form the basis for future optimization of the entire exhaust system to meet EU5 and beyond emission limits.

INTRODUCTION

Motorcycle and moped population is rising worldwide; in Europe a recent estimation [1] shows that the total vehicle population will be higher than 30 Million within 2010. Moreover, most of the 2 wheelers are used in the crowded centres of big cities where the contribution of motorcycle and moped exhaust gas to air pollution can't be under-estimated.

It becomes more and more important, in order to reduce air pollution, to use low CO_2 vehicles but it is also of primary importance to have tighter emission limits and control over the efficiency of exhaust after-treatment during the entire vehicle life. Recent studies carried out by AECC [2] show that with EU3 motorcycle and exhaust system it is almost possible, in some cases, to reach the EU5 values for automobile using an equivalent emission cycle. Up to today the European Commission has not yet approved the EU5 motorcycle emission limits and it is not clear if there will be an intermediate EU4 step. A probable scenario could be to have the same emission limits as the EU5 limits for 4 wheelers with durability requirements.

On the other hand, for the majority of EU3 motorcycles the request of higher catalyst efficiency along with new durability requirements will have in many cases considerable drawbacks such as cost increase and space constraint problems. Previous studies [3, 4] show that by using structured foils it is possible to increase the catalytic efficiency whilst keeping constant the substrate volume and PGM loading thus limiting these drawbacks.

The aim of this paper is to investigate advanced technology substrates in order to understand the possible contribution of the substrate to reach EU5 emission limits. In particular perforated foils (PE) and longitudinal structure (LS) substrate will be investigated to give a deeper understanding of the effect of turbulent like foil structure applied to motorcycle engines.

METALLIC SUBSTRATE DEVELOPMENT

Metallic substrates have been used for motorcycle and 3 Wheeler since the beginning of catalyst application. Easy canning and substrate robustness are two important characteristics that made the use of metallic substrate a “standard”. Among the metallic substrate producers, Emitec was the first to introduce in serial production S and SM winding type instead of spiral to increase mechanical durability. During recent years Emitec introduced the structured foils technology to improve the catalytic efficiency of metallic substrates with the scope to enhance the efficiency without increasing volume and total cost. KTM has been the first OEM worldwide to use PE substrate for motorcycle application (Super Duke 990 EU3, MY2007). In the following paragraph, a short overview of PE and LS technology principles will be given.

STRUCTURED FOILS TECHNOLOGY: ENHANCING TURBULENT FLOW

Laminar flow conditions occur behind the first section of the catalytic channel where the flow is not fully developed. Under laminar flow conditions the catalytic process is governed by the mass transfer (Figure 1).

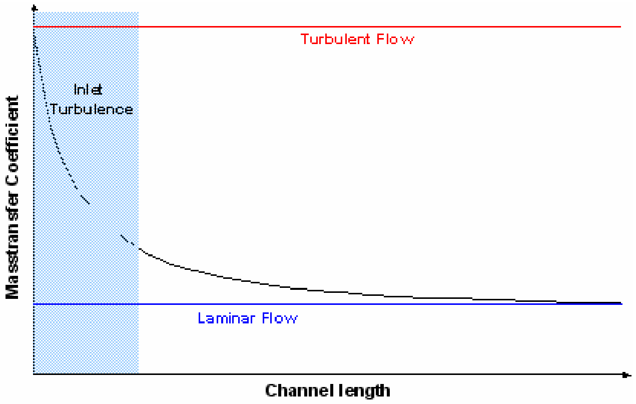

Figure 1. Mass transfer coefficient along the channel length.

The figure 1 shows how the mass transfer coefficient asymptotically approaches a low value just behind the inlet zone length. This means that a large part of substrate, where the mass transfer coefficient is too low or, in other words, the diffusion process of pollutants from channel core to reacting wall is too slow, is only partially used. One way to increase efficiency is the creation of turbulent flow conditions (Figure 2).

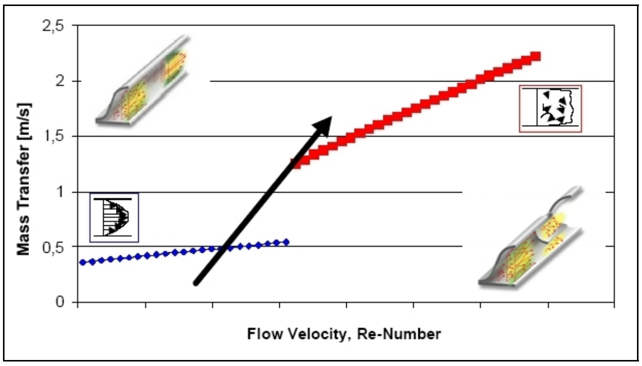

Figure 2. Qualitative increase of the mass transfer coefficient from laminar to turbulent.

A fully turbulent flow in the catalytic converter would result in a very high pressure drop. For this reason Emitec developed PE and LS substrates in which turbulence is generated locally. This approach not only increases the overall conversion efficiency but also has a positive effect on pressure drop in PE and LS catalysts.

PERFORATED FOIL TECHNOLOGY

Perforated foil (PE) technology has already been discussed in detail in previous papers [5, 6]. PE technology (Figure 3) uses perforated flat and corrugated foils to generate radial flow between adjacent channels. The loss of GSA (geometric surface area) is more than compensated for by the generation of locally turbulent flow. The development of perforated metal foils offers many advantages:

- homogeneous distribution of flow and pollutant concentrations
- reduction of heat capacity
- reduction of pressure drop
- Lower weight

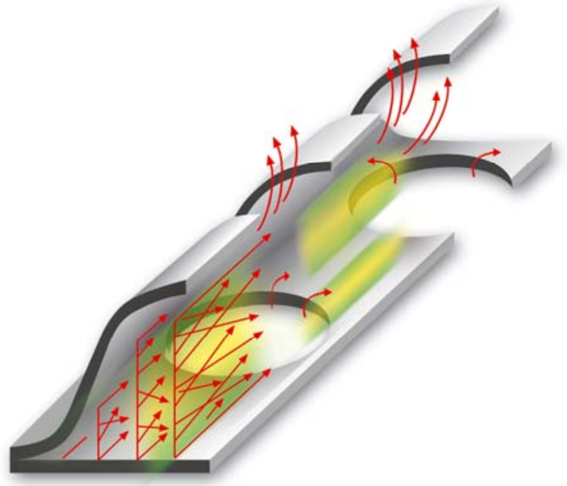

Figure 3. PE structure with flow details.

In contrast to standard catalysts (straight channel without any perforation or secondary structure), PE catalysts generate cross-flow, which gradually equalizes an inhomogeneous inlet flow. This exclusively turbulent compensating flow is driven by the radial pressure difference in the catalyst [7]. The result of this particular flow field backpressure in a PE catalyst is explained in Figure 4.

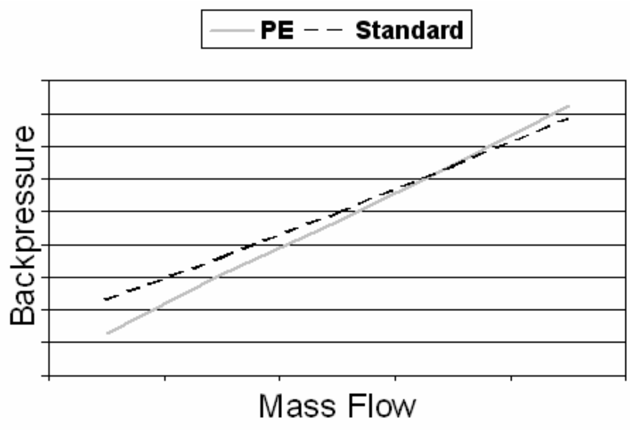

Figure 4. Qualitative backpressure representation of PE and standard catalysts.

Figure 4 shows how the two lines representing the backpressure of Standard and PE catalysts intersect at a certain value of mass flow. The figure is only qualitative because the intersection point depends on many parameters such as washcoat loading and distribution, cell density and foil thickness. Tests carried out on an uncoated substrate showed that in this case the lines intersect at channel Reynolds (Re) numbers between 1500 and 1900. At low Re numbers the PE substrate has always lower backpressure than standard substrates because the lower GSA and better internal flow distribution compensate for the increase of backpressure given by the locally turbulent flow conditions. At high Re numbers the backpressure increase due to turbulent-like condition is no longer compensated for and the total backpressure of a PE catalyst is higher than a standard substrate. Typical Re numbers in catalyst channels in real life applications have values for which PE catalysts have a lower backpressure than standard substrates.

LONGITUDINAL STRUCTURE TECHNOLOGY

The metallic longitudinal structure (LS) foil technology has been already extensively described and implemented in mass production in the automotive industry [5]. The LS technology consists of a counter corrugation applied on the sinusoidal part of the single channel in order to create some turbulent-like areas.

In an LS channel (Figure 5) as a result of the counter corrugation, i.e. the shovel, the laminar flow is broken and a new “turbulent like” zone is created: thereby the efficiency of the catalytic support is enhanced.

This explains the brand name of LS substrates, e.g. 200-400LS. The first figure (200) means the real cell density while the second (400) the cell density of a standard substrate that will have a comparable efficiency.

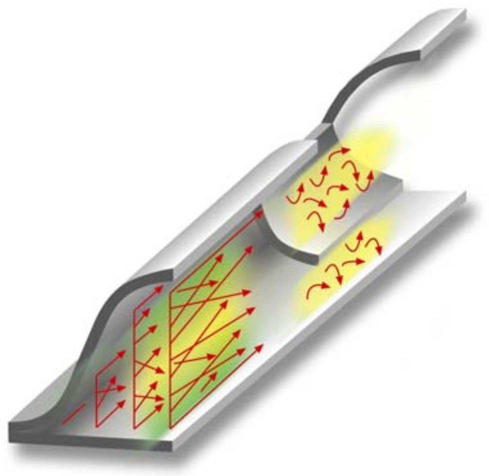

Figure 5. LS channel.

It has already been demonstrated how a metallic substrate with lower cell density but using LS technology can achieve the same conversion efficiency of a standard converter with higher cell density [8]. This property plays a key role for motorcycle application considering that a high efficiency can be reached using less material, i.e. foil quantity with positive effects on cost and weight compared to standard foils.

EMISSIONS RESULTS FROM PREVIOUS EXPERIENCES

A brief look into past experiences can provide important information to better design the test matrix. In a previous development programme [4], among others, two catalysts with the same dimensions (Ø70X50.8mm) and PGM Loading but different foil technology, one using PE and the second TS, have been tested.

TS was the first step towards turbulent-like substrates [9] and usually performs better than standard foils substrate. The corrugated foils of TS substrates are embossed with secondary micro-corrugations that run at an angle of 90 degrees to the direction of the flow. These micro-corrugations support the intense exchange of unconverted gases between the channel core and the walls, thereby locally increasing the mass transfer coefficient.

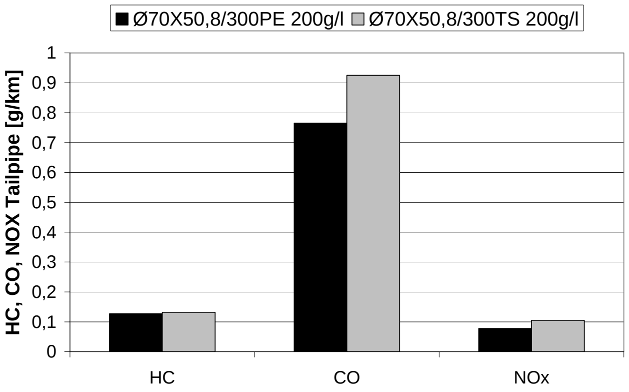

Figure 6. HC, CO and NOx tailpipe results of equal volume catalyst using PE and TS structure, NEDC.

Figure 6 shows that the use of PE turbulent-like structures decrease tailpipe CO by about 18% and NOx by about 22% while the reduction of HC is negligible.

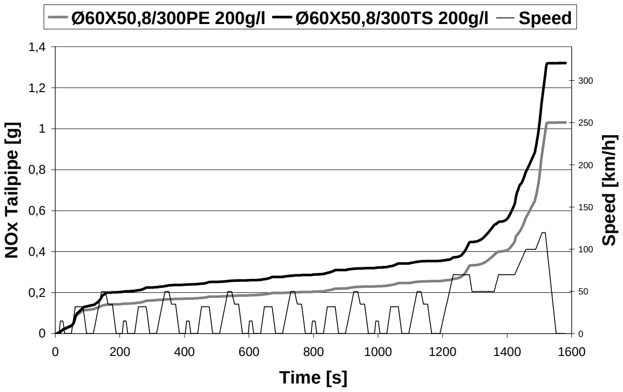

Figure 7. NOx tailpipe modal results of equal volume catalyst using PE and TS structure, NEDC.

The modal analysis [Figure 7] of second by second NOx tailpipe data shows that a PE catalyst has a faster light off, due to lower thermal mass, and maintains this advantage during the UDC part of emission cycle and increases the advantage versus TS catalysts in the EUDC parts where turbulence plays an important role.

A further experiment [3] was conducted in order to investigate the properties of LS technology comparing a 200 PE foil catalyst with a 200-400LS catalyst with 20% lower volume. The volume reduction was reached by shortening the substrate itself while the diameter remains constant. Both catalysts were coated using 120g/ft³ Pd only.

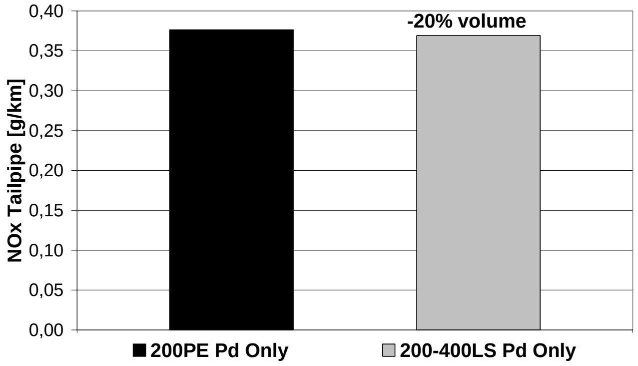

Figure 8. NOx tailpipe results of PE versus LS catalyst with ~20% lower volume, aged, NEDC.

Figure 8 shows the tailpipe NOx results of the aged catalysts. The ageing procedure is hydrothermal: 4 hrs. @ 980°C, 10% H_2O in air.

LS catalyst shows the same tailpipe NOx and HC emission level even if it has ~20% lower volume while LS catalyst has ~20% higher CO tailpipe emission level.

These promising results need to be more deeply investigated in order to understand what kind of technology is more suitable for EU5-Like emission limits.

TEST MATRIX

Two different strategies to meet EU5-Like emission standards have been used to design the test matrix. The first consists simply in increasing the catalytic volume keeping the inlet diameter constant (Ø 70mm). Three different catalytic converters have been tested (Table 1).

All catalysts in Table 1 have the same cell density (400cpsi) and the same foil structure (PE), therefore the substrate thermal mass increases proportionally to the length.

The scope of this test is to highlight the influence of volume, but also to investigate the cold start behaviour (influence of thermal mass) and to create a baseline database for the second set of experiments.

Catalyst	Length [mm]	Volume [l]	Thermal mass [J/K]
Baseline	74,5	0,287	74,0
Cat1	90	0,346	79,8
Cat2	101,5	0,391	82,4

Table 1. Catalyst characteristics for the first screening, all catalyst 400cpsi, PE technology, 70mm diameter, 50µm foil thickness.

The second set of experiments consists of equal volume catalysts with different foil technology and cell density. Each catalyst has a diameter of 70mm, a length of 101,5mm and a resulting volume of 0,391l (Table 2).

The objective of this experiment is to investigate the influence of high cell density and LS structure with regards to conversion efficiency.

All the catalysts measured have a Pt:Pd:Rh coating with 50g/ft³ PGM loading.

Catalyst	Cell density [cpsi]	Foil Technology	Thermal Mass [J/K]
Cat2	400	PE	82,4
Cat3	400	Std	138,6
Cat4	600	Std	165,7
Cat5	200-400	LS	91,9

Table 2. Catalyst characteristics for the second screening, diameter 70mm, length 101,5mm, 50µm foil thickness.

Backpressure of tested catalysts with 101,5mm length has been calculated with a simulation tool.

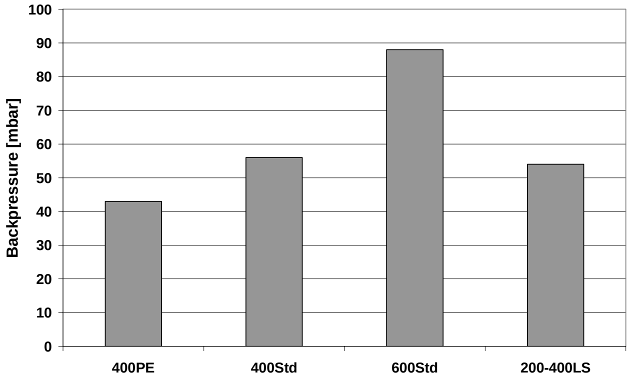

Figure 9. Calculated backpressure, 190kg/h, 850°C.

400PE has 23% and 51% lower backpressure compared respectively to 400Std and 600Std, while 200-400LS is equivalent to 400Std.

For motorcycle application another important parameter is the substrate weight.

The 400PE and 200-400LS substrate have the lowest weight while obviously the 600Std has the highest. The difference between the lightest and the heaviest substrate is slightly more than 150g.

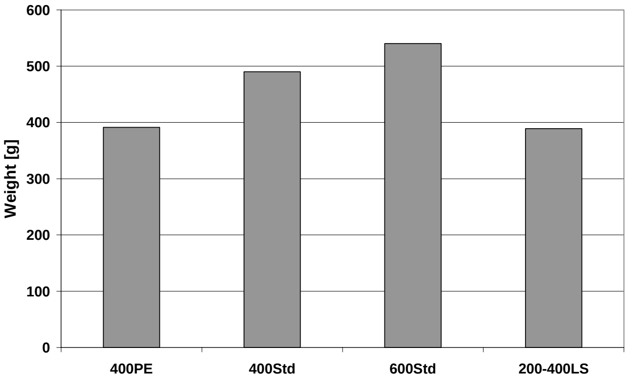

Figure 10. Weight of the 101,5mm long substrates.

TEST SET UP

The tests were carried out at KTM Sportmotorcycles AG in Mattighofen using a test bench specially developed for motorcycle emission measurements.

The single roller bench allows maximum speeds of 300 km/h and 100 kW of power peaking at 150 kW. A 110 kW blower delivers up to 105 m³/h of fresh air.

Modal engine out and tailpipe emissions are measured with a Horiba MEXA 7000 series.

The KTM 690 Enduro has a single cylinder four stroke engine. The displacement is 654cc (bore x stroke = 102 X 80mm) with a maximum power of 46.3 kW at 7500 rpm and a maximum torque of 64 Nm at 6000 rpm. The engine is equipped with electronic fuel injection, a lambda sensor, liquid cooling and four valves per cylinder and OHC.

Each catalyst was measured twice in de-greened condition and the measurements were checked again at the end of the test programme.

Room temperature was kept between 20°C and 22°C.

The test procedure for constant speed points is as follow:

- 60 sec. idling
- 120 sec. first gear at 20 km/h
- Constant point measurements, each 60 sec., point reported in Table 3
- 120 sec. idling

Point	Gear	Speed [km/h]
CP1	1	15
CP2	2	32
CP3	3	35
CP4	3	50
CP5	4	50
CP6	4	60
CP7	5	65
CP8	5	70
CP9	5	83
CP10	6	83

Table 3. Description of different constant load points.

A second test is carried out immediately after the first, then the motorcycle is cooled down at room temperature and the third and fourth test are carried out.

CONSTANT SPEED EMISSION RESULTS

The baseline catalyst has been measured first (Figure 11). While CO Efficiency remains high during the test, HC and NOx efficiency increases going from low load up to high load.

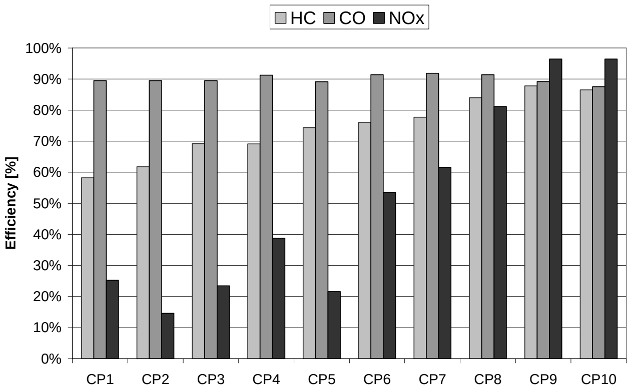

Figure 11. Baseline catalyst efficiency measured at different constant load points.

Poor HC and NOx efficiency at low load points should be related to lambda value.

For sake of brevity, only 3 points will be used for catalyst comparison: CP3, CP4 and CP9. The major difference, besides exhaust mass flow rate going from low value at CP3 up to a higher value at CP9, is the mean lambda value. CP3 has a slightly lean lambda value; CP4 is stoichiometric while CP9 is slightly rich. Temperature is always above 400°C, under this boundary condition the catalyst efficiency is mass transfer limited.

First of all, the influence of catalyst length has been investigated. Tested catalysts are reported in Table 1 while HC efficiency is reported in Figure 12. As expected the longer catalysts have better HC efficiency. The improvement in HC conversion efficiency in not proportional to the length increase, in fact the efficiency of the 101,5mm length catalyst is only slightly better than the efficiency of the 90mm length catalyst. On the other hand, there is a big increase in HC efficiency of the 90mm catalyst respective to the baseline that has a length of 74,5mm.

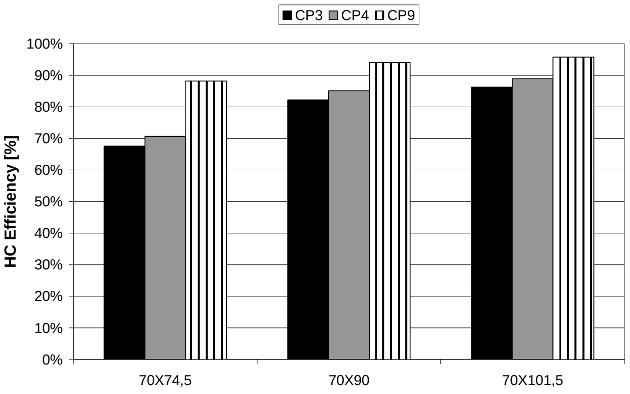

Figure 12. Influence of catalyst length on HC conversion efficiency.

This kind of asymptotic behavior can be explained considering that for the boundary condition of the test, i.e exhaust gas temperature, HC engine out, exhaust gas mass flow, lambda control, the volume of the 90mm length catalyst is enough to ensure almost the highest conversion efficiency.

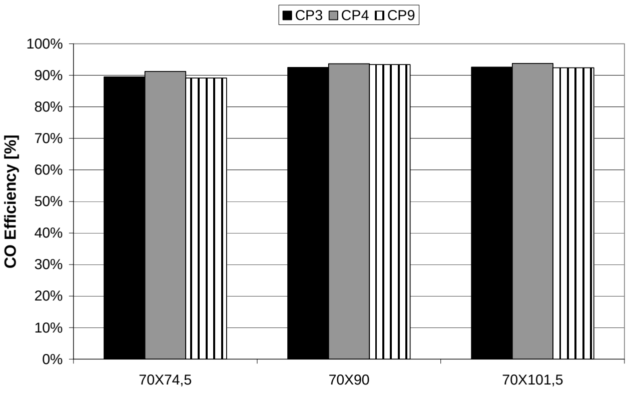

Figure 13. Influence of catalyst length on CO conversion efficiency.

CO conversion efficiency is reported in Figure 13. CO efficiency is very high even for the baseline system. Only a marginal increase is possible, but even for CO the influence of length is clear.

NOx efficiency is reported in Figure 14. In this case, the conversion efficiency increase is more related to volume, or length, increase, especially for the CP9 where the lambda value is slightly rich. The 90mm catalyst shows no efficiency increase in respect to the 74,5mm. This behaviour can be explained with the slightly different lambda value in the different tests as NOx conversion is very sensitive to this parameter and the very low absolute NOx engine out emission that leads to possible test to test variation.

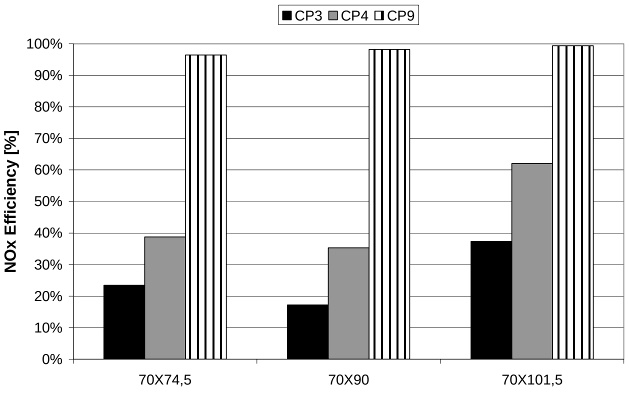

Figure 14. Influence of catalyst length on NOx conversion efficiency.

The second set of tests has been carried out comparing the baseline catalyst with a length of 74.5mm with four different catalysts all with length of 101,5mm with different cell density and foil structure (Table 2).

HC efficiency is reported in Figure 15. The efficiency of all 101,5mm long catalysts is very high in CP9 while some differences are visible for CP3 and CP4.

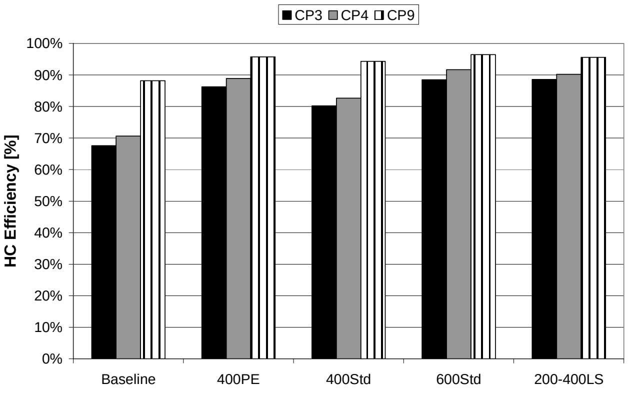

Figure 15. Influence of catalyst structure on HC conversion efficiency, baseline 400PE 74,5mm length.

The 400PE, the 600Std and the 200-400LS perform almost the same whilst 400Std is slightly worse in CP9 and remarkably worse in CP3 and CP4.

HC efficiency in mass transfer limited condition is then positively affected by turbulent like flow condition which, in the two structured foils catalysts (400PE and 200-400LS), compensates for the lack of GSA with respect to 600Std.

CO conversion efficiency is for every constant point and every tested catalyst very high (Figure 16).

Even in this case, the structured foils technology compensates for the lack of GSA, and all the 101.5mm long catalysts perform at the same efficiency level. Differently for the HC conversion efficiency, even the 400Std catalyst reaches the same efficiency level as the other tested catalysts.

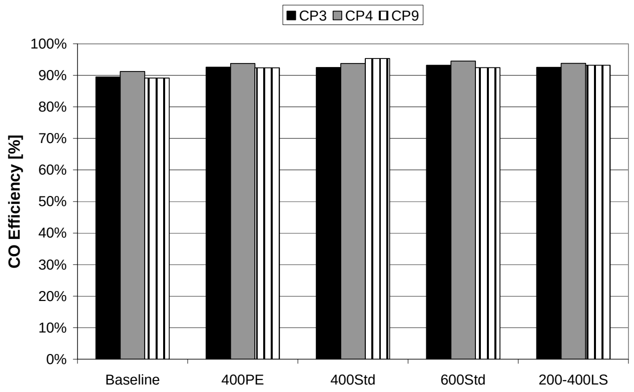

Figure 16. Influence of catalyst structure on CO conversion efficiency, baseline 400PE 74,5mm length.

NOx conversion efficiency is much more sensitive than HC and CO conversion efficiency to the different foils structures (Figure 17).

The PE technology catalyst is much more efficient than a standard technology equal volume catalyst: the better flow and pollutant distribution within the catalyst increases the overall efficiency in each of the constant points.

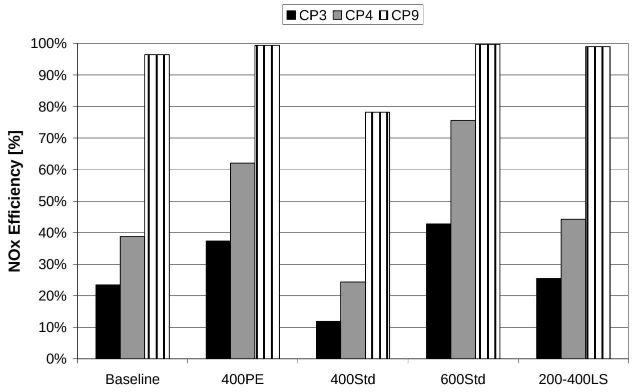

Figure 17. Influence of catalyst structure on NOx conversion efficiency, baseline 400PE 74,5mm length.

Moreover, even the shorter baseline catalyst (400PE, 74,5mm length) performs better than the 400Std.

Even for NOx conversion efficiency, PE and LS structures can compensate for the lower GSA with respect to 600Std in the constant point 9 whilst under CP3 and CP4 test conditions the 600Std performs better than the structured foils catalysts.

After this first set of tests it was decided to test further only the 400PE, 600Std and 200-400LS catalysts considering that the 400Std 101.5mm long has the lowest conversion efficiency.

Even if the 400PE 90mm long performed close to the same level as the 101.5mm, it was decided to stop the test considering that the larger catalyst is more interesting for EU5 and beyond.

WMTC EMISSION RESULTS

After the constant load points test, a set of WMTC test has been carried out.

While 400PE and 200-400LS catalysts show remarkable increase of HC and CO catalytical efficiency with respect to baseline, the 600Std catalyst is slightly worse (Figure 18 and Figure 20).

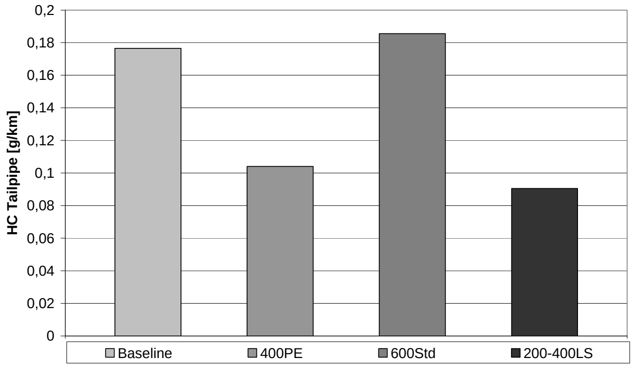

Figure 18. Influence of catalyst structure on HC conversion efficiency, WMTC.

The reason for that behaviour are the higher thermal mass of the 600Std [Table 2] that, under the boundary condition of this test, is a big penalty and the turbulent like flow condition of structured foils catalyst, that allow a very high conversion efficiency. A past experience [10] shows the influence of thermal mass during cold start for standard catalyst.

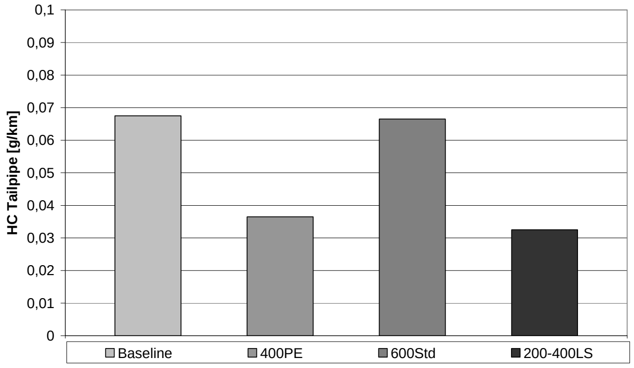

Figure 19. Influence of catalyst structure on HC conversion efficiency during WMTC cold start (first 600 seconds).

Figure 19 shows the HC tailpipe emission during WMTC light off phase of the tested catalysts. It is almost clear that the 600Std lights off slower than equal volume 400PE and 200-400LS and as fast as the baseline that has lower volume and much lower GSA.

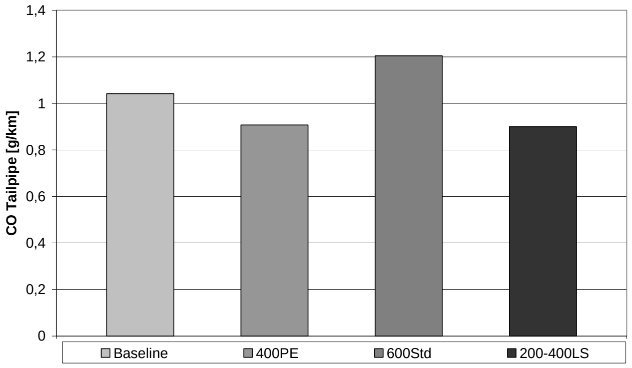

Figure 20. Influence of catalyst structure on CO conversion efficiency, WMTC.

A possible EU5 emission limits scenario could be 0,11 g/km for HC and 1,31 g/km for CO. By means of structured foils might be possible to reach these limits while the 600Std doesn't fulfill the HC requirements.

NOx efficiency on the other hand is much more related to catalyst volume and GSA, as the results in previous paragraph showed.

In this case, each tested catalyst performs much better than the baseline and the 600Std performs better than the 400PE and 200-400LS (Figure 21).

WMTC results confirm the constant load point results and the higher thermal mass of the 600Std doesn't play a big role.

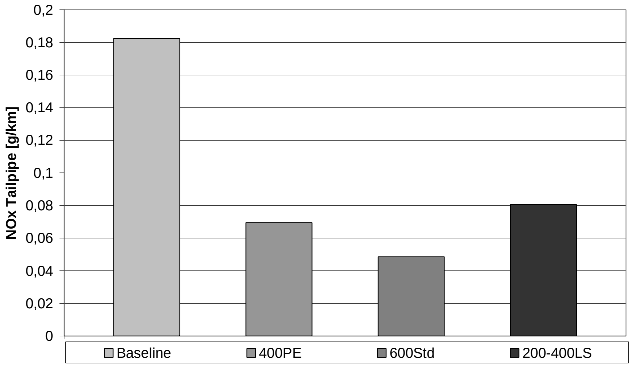

Figure 21. Influence of catalyst structure on NOx conversion efficiency, WMTC.

400PE catalyst performs better than 200-400LS confirming that the internal mixing effect of the PE structure increases the NOx conversion efficiency.

A possible EU5 limits might be 0,088 g/km, in this case all the tested catalyst fulfill this possible limit even if the 200-400LS would have almost no security factor.

CONCLUSIONS

Different catalyst using PE, Standard and LS structure have been tested using constant load points and WMTC test cycles.

The results of constant load points show that the 600Std performs better than 400PE and 200-400LS with the same catalytical volume.

WMTC results confirm this behaviour only for NOx efficiency while HC and CO conversion efficiency are much more influenced by thermal mass and turbulent like flow condition. 400PE and 200-400LS catalysts perform better than 600Std.

Taking into consideration not only the conversion efficiency but also substrate weight and backpressure, the overall performances of 400PE and 200-400LS are better than the standard technology catalyst.

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