

Innovative Metallic Substrate Technology to Meet Future Emission Limits

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Exhaust after-treatment systems will have to become increasingly efficient in order to comply with the strict emission limits that will apply in the European Union and worldwide in future. Moreover, space constraints, weight and low pressure drop are just some of the issues that have to be addressed by an EU III-compliant catalytic system. The development of metallic substrates over the past few years has shown that turbulent-like substrates increase specific catalytic efficiency. This has made it possible to enhance overall performance for a specific catalytic volume or reduce the volume while keeping catalytic efficiency constant. This paper focuses on the emission efficiency of standard, TS and PE metallic substrates. A simulation tool and flow bench measurements were used to develop a test matrix with catalyst similar pressure drop in order to examine different cell densities, substrate lengths and coating technologies. Emission tests were carried out on a KTM 990 Adventure motorcycle to evaluate substrates based on standard, TS and PE technology. The LC8 EFI engine is a state-of-the-art, typical high-performance engine with electronic injection and lambda sensor control. Results confirm that compared to standard catalysts PE technology increases the emission efficiency of the catalyst without any adverse effect on pressure drop. On the other hand, TS technology as applied in high mass-flow engines is less efficient than PE technology, provided the PE and TS substrates have the same pressure drop. Engine performance measurement has been carried out at the end of emission test to check the influence of catalyst pressure drop on power output.

Keywords: Emission limits, catalyst pressure drop, catalyst volume, turbulent structure

1. INTRODUCTION

Catalyst systems will have to become even more efficient over the next few years in order to meet strict emission legislation. Two major approaches were developed on the basis of past experience with four-wheels vehicles: The first involves increasing the cell density or the volume of the catalyst. This approach has some drawbacks in terms of system cost and space constraints, which make it very difficult to apply this principle to two and three-wheelers. The second and more recent approach involves the use of turbulent substrates to increase specific catalytic efficiency and reduce total system costs [1, 2]. Recent studies demonstrated that this approach can be applied to two and three-wheelers without any major drawbacks [3, 4]. High-performance sports engines for motorcycles are a very important area of application where system costs, space constraints, catalytic efficiency and pressure drop play a crucial role in maintaining high power output. This paper presents the tests carried out on different foil structures, which compare TS (transversal structure) and PE (perforated foils) catalysts to standard technology using different substrate lengths to keep pressure drop similar.

2. TURBULENT-LIKE SUBSTRATES

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 determined by the mass transfer (Fig. 1).

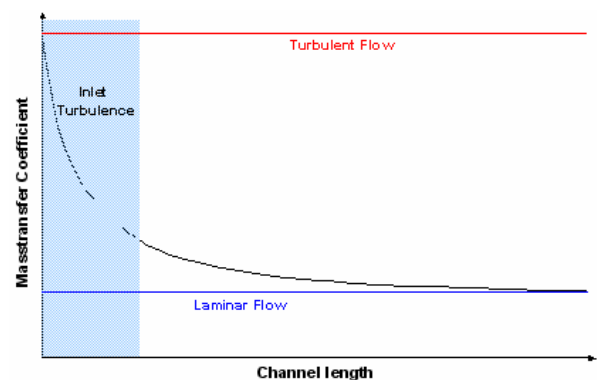


Figure 1 Mass transfer coefficient along the channel length

The figure shows how the mass transfer coefficient asymptotically approaches a low value just behind the inlet length. One way of increasing efficiency is to create turbulent flow conditions (Fig. 2).

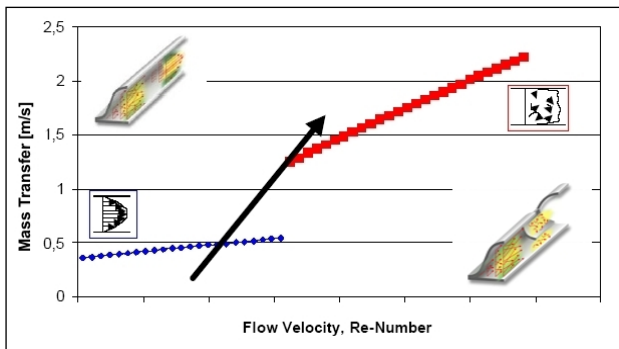


Figure 2 Qualitative increase of the mass transfer coefficient from laminar to turbulent.

A fully turbulent catalytic converter would have very high pressure drop. For this reason Emitec developed turbulent TS and PE catalysts in which turbulence is generated locally. This approach increases overall efficiency while having only a minor effect on pressure drop in TS catalysts and even reducing pressure drop in PE catalysts under specific flow conditions.

3. TRANSVERSAL STRUCTURE TECHNOLOGY

The TS design has entered commercial production and is widely used in mass-produced components for automotive applications. 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 (Fig. 3). These micro-corrugations support the intense exchange of unconverted gases between the channel core and the walls, thereby locally increasing the mass transfer coefficient.

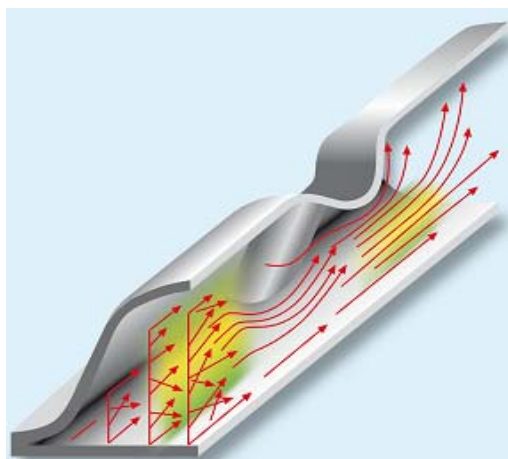


Figure 3 TS structure with flow details

Previous [3, 5] experience shows that it is possible to reduce the volume through the use of TS technology. TS technology was chosen for the purpose of this paper in order to

gain a better understanding of the properties of catalytic activity and of pressure drop performance using typical motorcycle cell densities and dimensions.

4. PERFORATED FOIL TECHNOLOGY

Perforated foil (PE) technology has already been successfully applied in the mass production of components for a variety of applications and has been discussed in detail in previous papers [7, 8]. PE technology (Fig. 4) uses perforated flat and corrugated foils to generate radial flow between adjacent channels. The loss of GSA (geometrical surface area) is more than compensated by the generation of turbulent flow. The development of perforated metal foils offers a number of advantages:

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

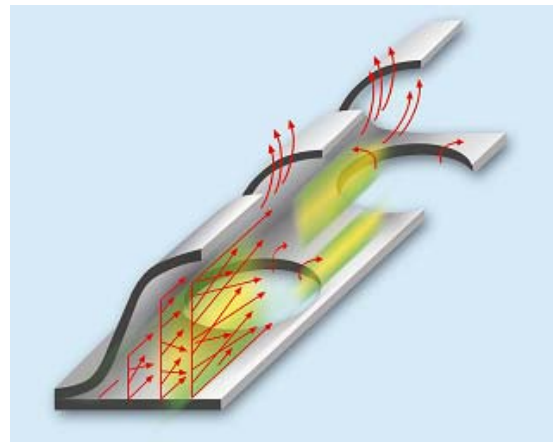


Figure 4 PE structure with flow details

4.1 DETAILS OF FLOW PROPERTIES

Pressure drop Δp caused by pressure loss in catalysts with a length ΔL is generally determined by:

$$-\frac{\Delta p}{\Delta L} = \zeta \frac{\rho}{2} u^2 + \alpha \mu u \quad \text{equation (1)}$$

where ζ and α are the pressure drop coefficients, ρ is density, μ is dynamic viscosity and u is flow velocity. The squared term on the right-hand side of the equation describes the pressure drop caused by the turbulent flow, which occurs when the exhaust gas flows into the catalyst channels and when it flows out of the catalyst channels. The pressure drop caused by the turbulent entrance flow into the catalyst channels until the laminarisation of the flow has also been taken into consideration. The pressure drop caused by the laminar flow generated as the exhaust gas passes through the catalyst channels is represented by the linear term on the right-hand side of the equation.

In catalysts with PE foils the perforation of the channel walls reduces the pressure drop coefficient α derived from the

laminar flow and simultaneously increases the pressure drop coefficient ζ derived from the turbulent flow. Since the laminar pressure drop is generally greater than the turbulent pressure drop as the flow passes through the catalyst the overall result may be that the pressure drop in PE foil catalysts is smaller than in standard catalysts. As a first approximation it is safe to assume that the pressure drop caused by the laminar flow is reduced in proportion to the reduction of the channel wall surfaces:

$$\alpha_{PE} = (1 - \Psi_{PE})\alpha$$

equation (2)

with:

$$\Psi_{PE} = \frac{A_{PE}}{A}$$

where α_{PE} is the pressure drop coefficient of the PE foil catalyst, α is the pressure drop coefficient of the standard catalyst and Ψ_{PE} is the perforation (= perforated surface A_{PE} in relation to the total foil surface A).

In return, the pressure drop caused by the turbulent flow increases since expansion losses occur when the exhaust gas flows out of the catalyst channels into the caves. Added to this are the pressure drop that occur when the flow re-enters the channels.

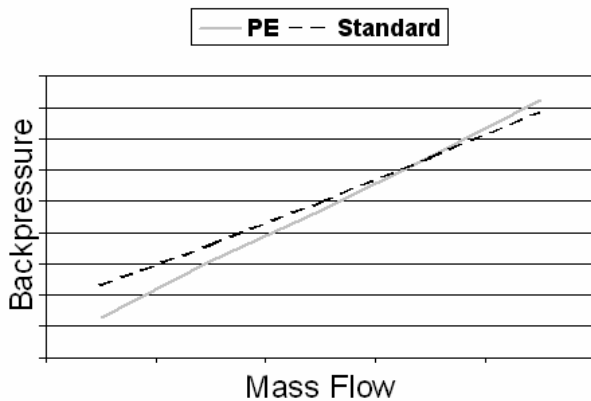


Figure 5 Qualitative backpressure representation of PE and standard catalysts.

In contrast to standard catalysts, PE catalysts generate cross-flow, which gradually evens out an inhomogeneous inlet flow. This exclusively turbulent compensating flow is driven by the radial pressure difference in the catalyst [6]. The results of this particular flow field in a PE catalyst are explained in Fig. 5.

Fig. 5 shows how the two lines intersect at a certain volume 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 numbers between 1500 and 1900.

5. TEST MATRIX

The test matrix was developed in order to examine different substrate lengths, foil technologies and washcoat thickness at a similar pressure drop (Table 1).

Other important parameters such as diameter (70 mm) and foil thickness (50 μm) have been kept constant in order to minimise secondary effects.

Cat.	Lenght [mm]	Cell density [cpsi]	Foil type	W/C Loading [g/l]	PGM Loading [%]	Volume [l]	Vol. Reduction [%]
VP0	74.5	400	PE	68	50	0.287	0
VP2	50.8	300	PE	200	100	0.196	32
VP3	65	300	Standard	100	100	0.25	13
VP4	60	300	Standard	200	100	0.231	19
VP5	65	300	TS	100	100	0.25	13
VP6	50.8	300	TS	200	100	0.196	32

Table 1: Test matrix

Two different substrates were tested for each type of foil design.

Another very important parameter is the PGM loading. The total PGM amount of catalysts VP2 to VP6 is the same. The PGM loading of VP0 is 50% less in order to gain a better understanding of the effects of low PGM loading on PE technology. Each catalyst was coated with Pt, Pd and Rh using technology developed by Heraeus.

The backpressure produced by the coated substrates is reported in Fig. 6. The backpressure was measured at 75 kg/h and 100°C giving a channel Reynolds number that is comparable to real-life operating conditions at maximum power.

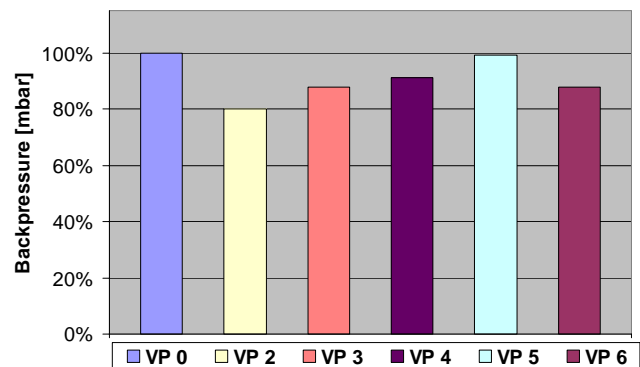


Figure 6 Backpressure of the tested catalysts measured at 75 kg/h, 100°C

It is important to note that the VP0 catalyst with 400 cpsi PE foils produces almost the same backpressure as the VP3 with 300 cpsi standard foils and a 13% smaller volume, the VP4 with 300 cpsi standard foils and a 19% smaller volume, the VP5 with 300 cpsi TS foils and a 13% smaller volume and the VP6 with 300 cpsi TS foils.

By contrast, the backpressure of the VP2 catalyst with a thicker washcoat and a 32% shorter matrix is 20% lower.

Another important parameter for sport motorcycle, where the total motorcycle weight should be kept as lower as possible, is the catalyst weight. In Fig 7 the weight of the uncoated and

coated catalysts is reported.

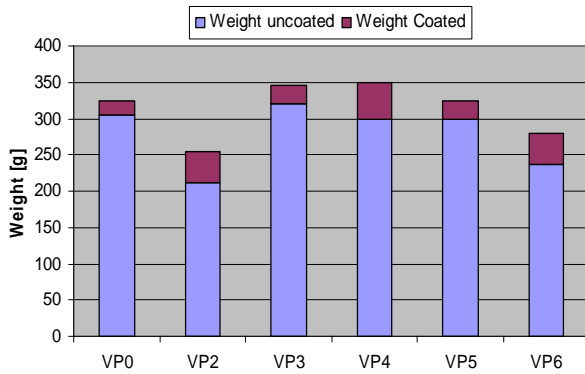


Figure 7 Weight of uncoated and coated catalysts

The VP0 catalyst, even with the higher volume, has a substrate weight comparable to the standard and TS technology, excepting VP6 that has 32% lower volume.

Substrate weight and thermal mass have also a major influence on cold start performances.

6. EMISSION MEASUREMENTS

6.1 TEST SETUP

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

The single roll bench allows maximum speeds of 300 km/h and 100 kW of power peaking at 150 kW.

A 110 kW blower delivers up to 10^5 m³/h of fresh air.

Modal and bag emissions are measured with a Horiba MEXA 7000.

The KTM 990 Adventure has a V2 75° four-stroke engine. The displacement is 999 cc (bore x stroke = 101 x 62.4 mm) with a performance of 72 kW at 8500 rpm and 95 Nm at 6500 rpm. The engine is equipped with electronic fuel injection, a lambda sensor, liquid cooling and four valves per cylinder with DOHC.

Each catalyst was measured three times in fresh condition and the measurements were checked again at the end of the test programme. Both modal and bag measurement were carried out.

Room temperature was kept between 20°C and 22°C. After each measurement the motorcycle was left cooling down until the oil temperature reached the room temperature.

Measurement errors are reported in the form of bar diagrams. The errors are within the acceptable tolerance.

Modal data is the mean value of the three measurements.

6.2 BAG RESULTS

The overall performance of the VP0 catalyst is better than that of the other catalysts. A particularly interesting result was that the HC emissions of the VP0 catalyst were between 16% and 31% lower than others catalyst (Fig. 8).

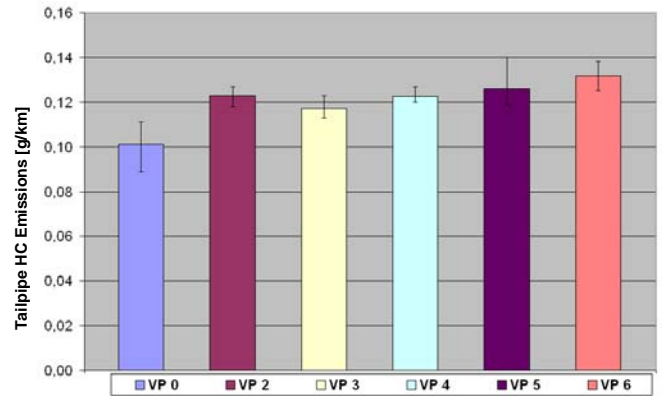


Figure 8 Tailpipe HC emissions

VP2 performance with regard to CO emissions is comparable to VP0. The other catalysts produce 13% to 28% higher CO tailpipe emissions than the VP0 and VP2 catalysts (Fig. 9).

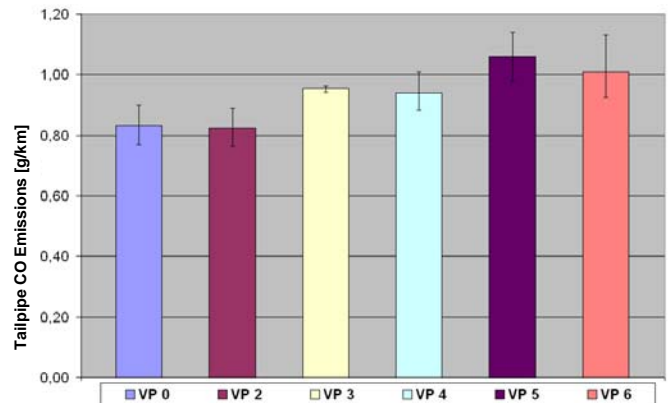


Figure 9 Tailpipe CO emissions

The reason of the higher tailpipe emission of VP6 compared to VP2 is the better light off performance of VP2 due to lower thermal mass (fig. 14)

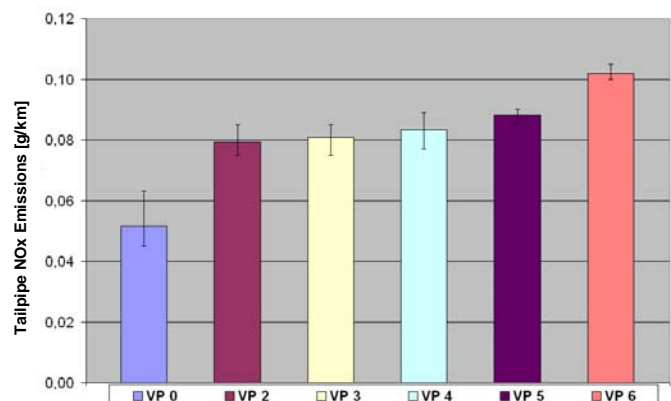


Figure 10 Tailpipe NOx emissions

The NOx results clearly demonstrate the advantages of PE technology. The VP0 catalyst produces 34% to 49% lower tailpipe emissions. The PE structure and the catalyst volume play an important role in this case (Fig. 10).

The reason why VP0 has ~38% lower NOx as VP2 emission is to be found in the volume difference between the two catalyst.

A comparison between the VP2 catalyst (300 cpsi, PE technology) and the VP6 catalyst (300 cpsi, TS technology) with identical volumes and washcoat thickness shows that the PE catalyst produces 22% lower NOx tailpipe emissions. In this case the better emission performance of VP2 is given by PE technology.

6.3 MODAL RESULTS

For the sake of brevity this section concentrates on an analysis of the most important results of EU3 emission cycle.

(1) Comparison between VP0 and VP3

The HC light-off performance of the two catalysts is comparable and their conversion efficiency is similar up to a vehicle speed of 70 km/h. At speeds exceeding 70 km/h the PE catalyst was more efficient than the standard catalyst. The reason for this is the higher efficiency of the PE structure at high mass flow rates when the turbulent effect and the bigger volume of the PE catalyst play an important role (Fig. 11).

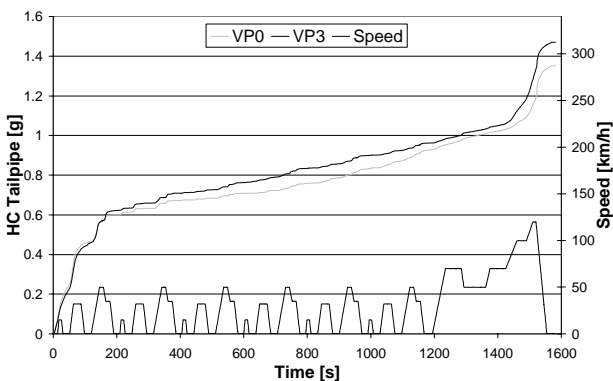


Figure 11 Modal HC emissions of VP0 and VP3 catalysts

The CO efficiency of the two catalysts is identical during light-off but starting from the beginning of the second hill the PE catalyst becomes more efficient.

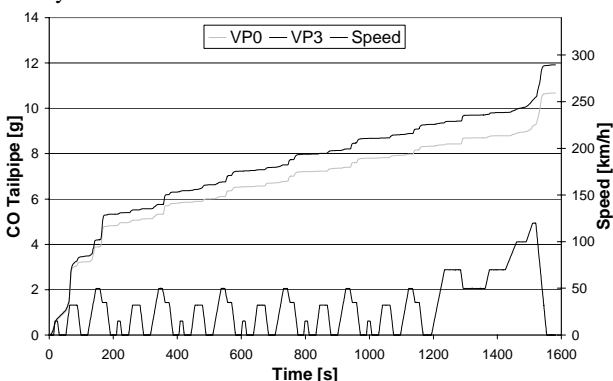


Figure 12 Modal CO emissions of VP0 and VP3 catalysts

Even in this case PE technology offers considerable advantages in terms of internal flow mixing and thermal mass (Fig. 12) bearing in mind that PE catalysts have a 50% lower PGM content.

NOx results also confirm the advantages of PE structures. PE catalysts improve emission efficiency during light-off (Fig.13).

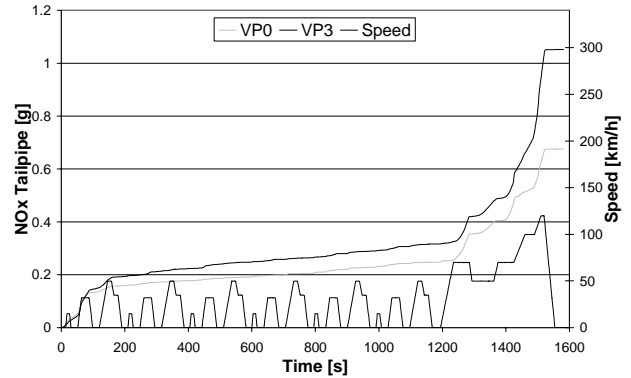


Figure 13 Modal NOx emissions of VP0 and VP3 catalysts

The advantages of PE catalysts remain more or less constant during the entire emission cycle but when the exhaust mass flow increases the efficiency of PE catalysts increases as well.

(2) Comparison between VP2 and VP6

The HC efficiency of the two catalysts is almost identical. It is interesting to note that the lower thermal mass of the PE catalyst and the internal mixing of the exhaust gas have an effect on CO light-off (Fig. 14).

The light-off advantages rise to a value of 23% during the emission test.

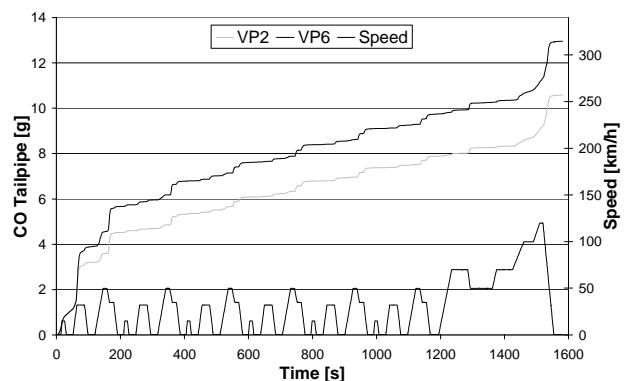


Figure 14 Modal CO emissions of VP2 and VP6 catalysts

The same applies to the conversion of NOx (Fig. 15).

This case also clearly demonstrates the increasing advantages of PE catalysts during the high mass flow phase of the emission cycle. This result also shows how turbulent flow inside the catalyst produces better emission performance in systems with the same volume and the same PGM content.

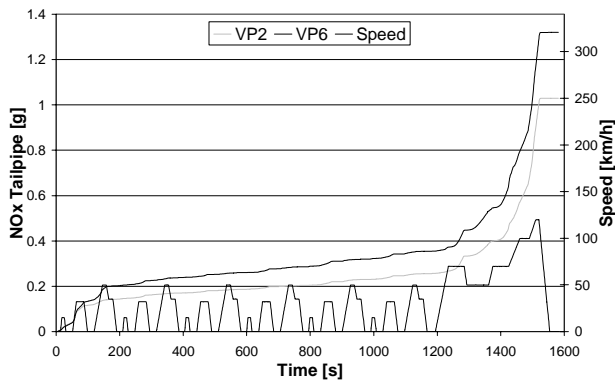


Figure 15 Modal NOx emissions of VP2 and VP6 catalysts

(3) Comparison between VP0 and VP2 - NOx

In chapter 6.2 commenting Fig. 10 the better NOx performance of VP0 compared to VP2 has been explained by means of the higher catalyst volume of VP2.

Looking at modal results, Fig. 16 points out very well the effect of volume on NOx conversion.

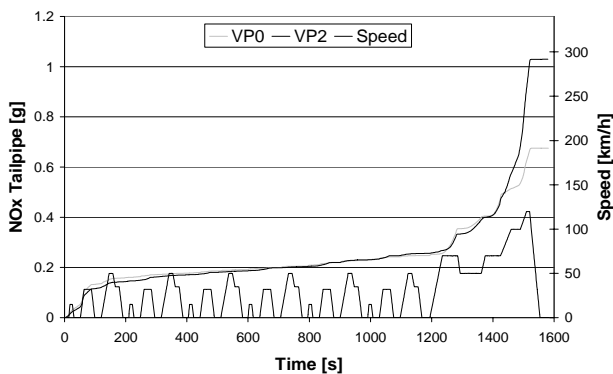


Figure 16 Modal NOx emissions of VP0 and VP2 catalysts

During the cold start up to warm operation phase the VP2 catalyst performs as well as the VP0 with 32% higher volume. Only when the space velocity increases after 1400 sec. the VP0 performs much better.

7. ENGINE PERFORMANCE MEASUREMENTS

At the end of the emission test measurement, engine performances have been re-checked with all different catalysts.

Fig. 17 shows very clearly that the slightly different pressure drop of the six tested catalysts has almost no effect on engine performance.

This result shows that using PE technology (VP0) it is possible to increase the volume and therefore the emission efficiency without any drawbacks in terms of engine performance.

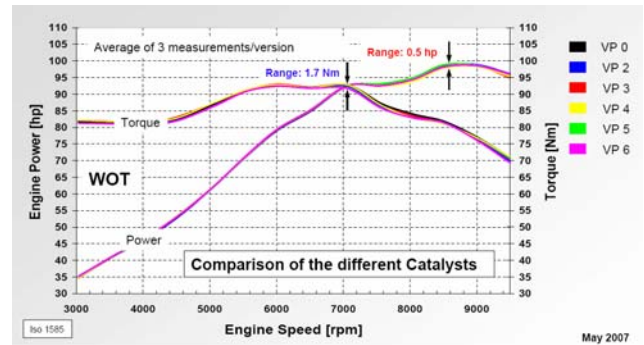


Figure 17 Engine performance measurements

8. CONCLUSIONS

Six different catalyst using standard, PE and TS foil technology have been tested with regards to emission efficiency and influence on engine performances. The tested catalysts have similar pressure drop at mass flow rate representative of max power condition.

- (1) PE technology (VP0) delivers superior emission performance at a lower PGM loading (~50%) and at similar pressure drop as standard and TS catalysts.
- (2) PE technology (VP2) delivers superior emission performance with the same PGM loading and ~9% lower pressure drop compared to TS catalysts with the same volume (VP6).
- (3) The slight pressure drop variation of the different catalyst has no influence on engine performance.
- (4) PE Catalysts have a weight advantage.

9. ACKNOWLEDGMENTS

The authors would like to thank Mr. Uwe Endruschat, Mr. Ansgar Wille and Mr. Hans Hildenbrand of W.C. Heraeus GmbH for their support.

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