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Changing the Substrate Technology to met future Emission Limits

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ABSTRACT

Future stringent emission legislation will require high efficient catalytical systems. Along with engine out emission reduction and advanced wash coat solution the substrate technology will play a key role in order to keep system costs as low as possible.

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 (Transversal Structure) and LS (Longitudinal Structure) metallic substrates. In a first measurement program, standard TS and LS substrates have been compared using a 150cc 4 Stroke engine in dynamic (ECE R40) conditions. In a second test standard and LS substrate have been tested.

Both TS and LS technologies show advantage compared to standard technology but have different application fields: TS is a cost effective solution for next emission limits while LS is a possible solution for future stringent 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 centers 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 CO2 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 a reduction of about 50% of EU3 limits with 30.000 km 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 in metallic substrates 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 itself to reach EU4 emission limits. In particular transversal structure (TS) and longitudinal structure (LS) metal supports will be investigated to give a deeper understanding of the effect of turbulent like foil structure applied to motorcycle engines with different displacement.

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". Emitec has been the first to introduce in serial production S and SM winding type instead of spiral wound substrates to increase mechanical durability. During recent years Emitec introduced the structured foils technology to improve the catalytic efficiency of metallic substrates without increasing volume and total cost. In the following paragraph, a short overview of TS 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).

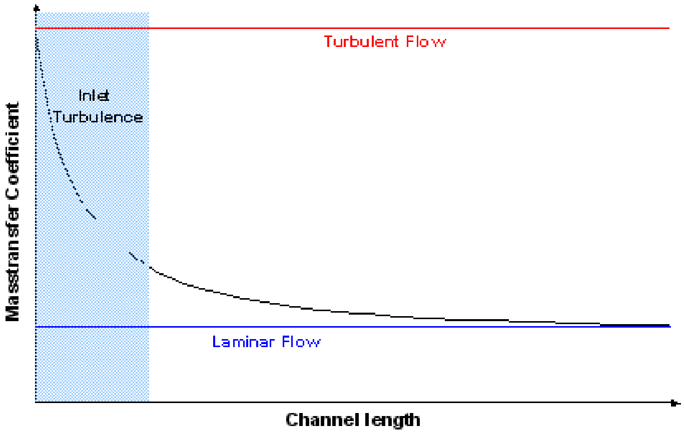

Figure 1. Mass transfer coefficient along the channel length.

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).

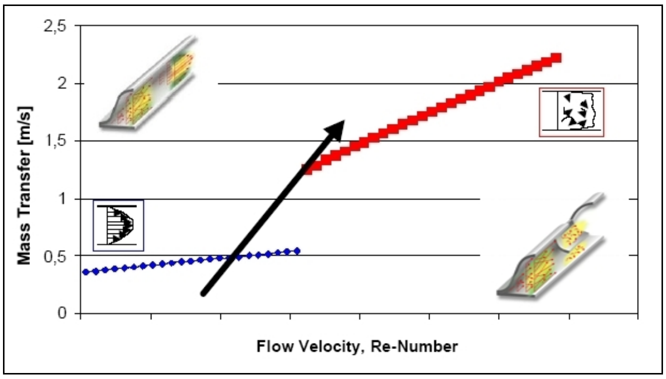

Figure 2. Qualitative increase of the mass transfer coefficient from laminar to turbulent.

A fully turbulent flow in the catalytic converter would result in a very high pressure drop. For this reason Emitec developed TS 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 TS and LS catalysts compared with higher standard cell density with comparable conversion efficiency.

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 (Figure 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.

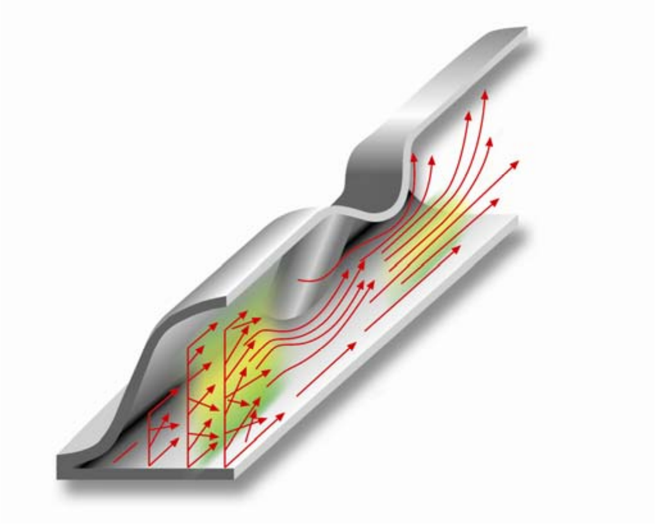

Figure 3. TS structure with flow details.

Previous [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.

LONGITUDINAL STRUCTURE TECHNOLOGY

The metallic longitudinal structure (LS) foil technology has been already extensively described and implemented in mass production in the automotive industry [6]. 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 4) 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) represents the real cell density while the second (400) represents the equivalent cell density where the secondary corrugation is located in the channel. The higher figure also represents the cell density of a standard substrate that will have a comparable efficiency.

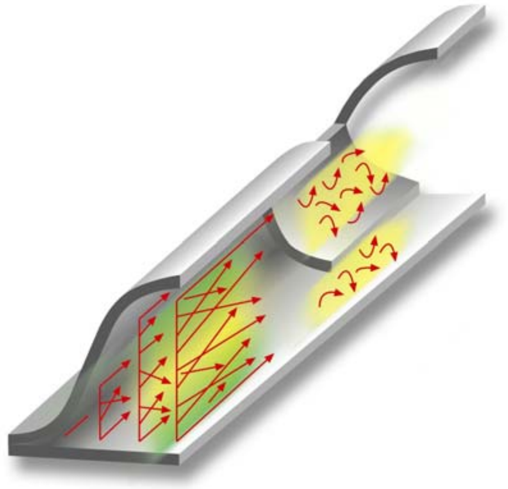

Figure 4. LS structure with flow details.

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 [7]. 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.

TEST OF TS AND LS STRUCTURE ON TYPICAL 150CC MOTORCYCLE

The use of newly developed turbulent catalysts was tested in several small capacity engine applications [8], e.g. stationary engines or small capacity scooter engines. Further development was going on in the representative state of the art one cylinder 4 stroke 150 cm³ motorcycle (air cooled, carburetor, 5 gears, 210kg reference gross weight with 9.8kW at 8000rpm) developed and homologated for the effective Indian legislation Bharat II.

Several types of turbulent catalysts were mounted in the original exhaust muffler and compared with the standard catalyst substrate. The comparison was carried out on the chassis dyno test bench for European Driving Cycle ECE R40. The exhaust emission components like hydrocarbons, nitrogen oxides and carbon monoxide were collected separately in emission bags for warm-up and homologation cycle. This method allowed an extensive analysis of the cold start and homologation phase of the tested catalyst technologies for both emission cycles. On-line recorder data (temperatures in exhaust muffler, emission components and air excess ratio), measured during dynamic tests on the chassis dyno test bench, provided an insight into cold start behavior and exhaust emission components progression over the measured emission test cycle during acceleration and deceleration sections of the vehicles, and gave detailed information about light-off characteristics of the different catalyst technologies.

Based on the results of the untreated and treated exhaust gas emissions, measured for standard and turbulent catalytic converters on the representative motorcycle, the qualification of each after treatment catalyst technology concerning effective and future Indian and European exhaust emission regulations could be discussed.

Testing several substrates under the same condition is a challenge for the measuring configuration, especially when the expected differences of each testing subject are small. Therefore a special exhaust muffler configuration was designed with the possibility to change substrates in the exhaust pipe several times and at the same time assure complete tightness of the exhaust system between exhaust muffler and catalyst (Figure 5). The original layout, i.e. pipe lengths and chamber design, of the muffler was not changed. In addition, five temperature sensors (three before catalyst, two after catalysts) were applied in the exhaust system. For the exhaust gas mixture condition analysis an oxygen sensor was mounted in the exhaust muffler.

Figure 5. Exhaust system setup on tested vehicle.

To ensure the same testing conditions for all treated substrates no changes on the vehicle engine were made. The secondary air system of tested vehicle was not modified.

Tested catalysts are reported in Table 1.

Catalyst	Cell Density [cpsi]	Technology	Length [mm]	Volume [l]	Thermal mass [J/K]	PGM Loading [g/ft^3]
100Std	100	Standard	60	0,075	27	56
100TS	100	TS	60	0,075	27	40
100LS	100	LS	60	0,075	27	40

Table 1. Catalyst characteristics, 40mm diameter, 5:1 Pt:Rh PGM Loading.

100 Standard catalyst has a 56 g/ft³ 5:1 Pd:Rh coating while for the two structured foils catalyst the loading has been lowered to 40 g/ft³ (28% lower).

EMISSION RESULTS

Emission results are reported in Figure 6.

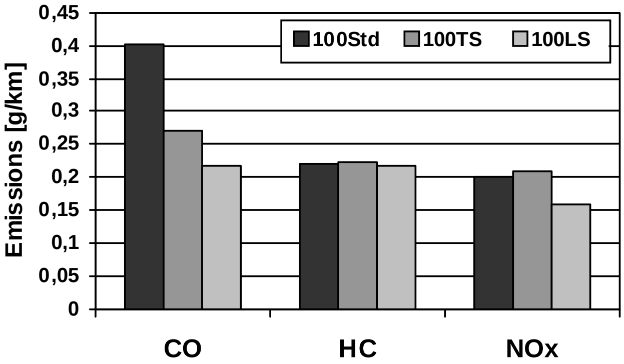

Figure 6. Emission results of the tested catalyst in ECE R40 Cycle.

Despite the lower PGM Loading (-28%) of TS and LS catalysts, both show better CO and comparable HC conversion efficiency compared to 100 Standard. LS catalyst shows moreover even a better NOx conversion efficiency than 100 Standard.

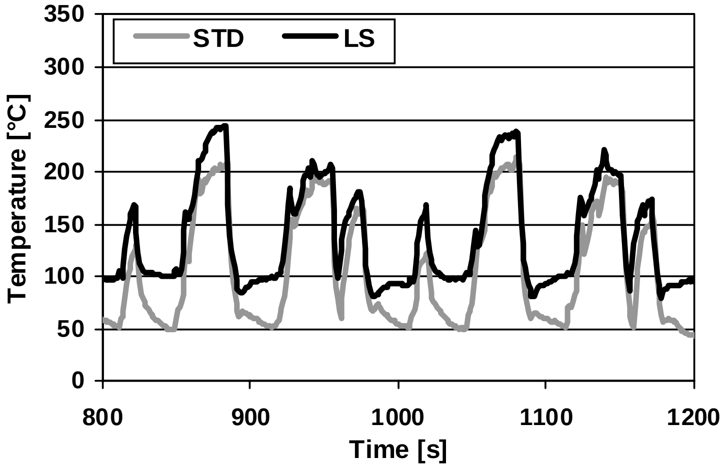

Figure 7. Emission Temperature difference between catalyst inlet and outlet.

Figure 7 shows the temperature difference measured between catalyst inlet and outlet, the bigger this difference the higher is the conversion efficiency (there is no thermal mass difference between 100Std and 100LS substrate). For sake of clarity, only the last 400 seconds of the emission cycle are reported. It can be observed how the LS catalyst has always a higher temperature difference than the 100cpsi Standard. 100 cpsi TS catalyst has a similar behavior.

This results confirm that TS and LS technology increases the conversion efficiency even with lower PGM Loading allowing even a cost reduction.

TEST OF LS STRUCTURE ON TYPICAL 650CC MOTORCYCLE

After the principal differences between turbulent foil substrates and laminar substrates have been assessed in the tests reported in the previous paragraph focused on medium size engine displacement, an application-oriented measurement campaign has been carried out with a 650cc motorcycle. The main target of this part of the work is to illustrate the application strategies of turbulent substrates with particular focus on cell density variations thus on thermal mass influence on overall performance.

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 m^3/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. A muffler design similar to that used in previous test was used in order to ensure measurement repeatability.

Each catalyst was measured twice in de-greened condition and the measurements were checked again at the end of the test program. 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 2
- 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 2. 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.

Catalyst	Technology	Length [mm]	Volume [l]	Thermal mass [J/K]
400Std	Standard	101,5	0,346	138,6
600Std	Standard	101,5	0,346	165,7
200-400LS	LS	101,5	0,346	79,8

Table 3. Catalyst characteristics for the first screening, 70mm diameter, 50µm foil thickness.

Tested catalysts are reported in Table 3, each catalyst has the same inlet diameter (70mm) and length (101,5mm), the LS catalyst has a much lower thermal mass due to the lower cell density.

200-400LS catalyst has a 39% lower backpressure than 600 standard calculated at 190kg/h, 850°C.

CONSTANT SPEED EMISSION RESULTS

The baseline catalyst has been measured first (Figure 8). While CO Efficiency remains high during the test, HC and NOx efficiency increases going from low load up to high load.

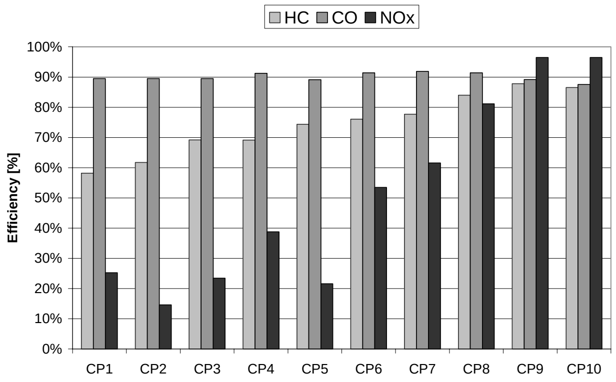

Figure 8. Baseline catalyst efficiency measured at different constant load points.

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.

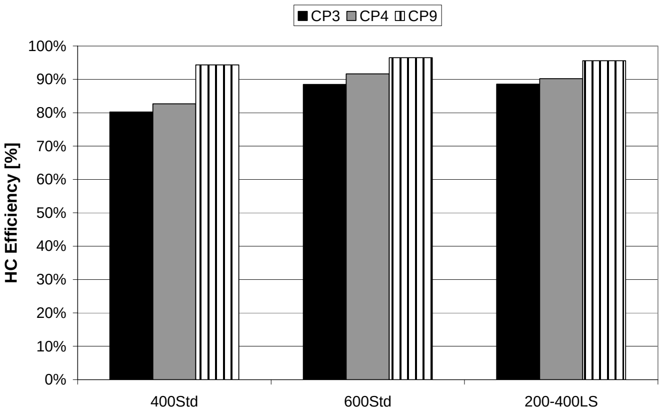

Figure 9. Influence of catalyst structure on HC conversion efficiency.

For each of the three measured points, LS catalyst shows HC conversion efficiency comparable to 600cpsi (Figure 9). It should be underlined also that in slightly rich condition the LS catalyst has almost 10% higher efficiency than a 400Std that could be an advantage during real life operation.

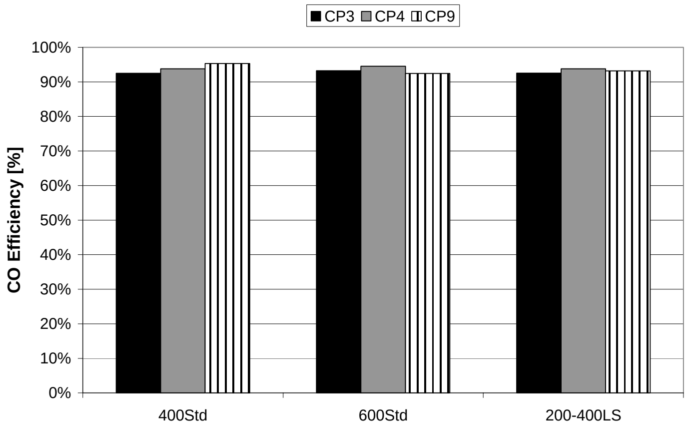

Figure 10. Influence of catalyst structure on CO conversion efficiency.

CO conversion efficiency is reported in Figure 10. CO efficiency is very high even for the 400Std catalyst, therefore only a marginal increase is possible.

NOx efficiency is reported in Figure 11. In this case, the conversion efficiency increase of LS technology compared to 400Std catalyst is very clear for all three constant points. On the other hand, the higher contact surface of the 600Std plays a key role in NOx conversion efficiency resulting in higher NOx conversion at slightly rich and stoichiometric points.

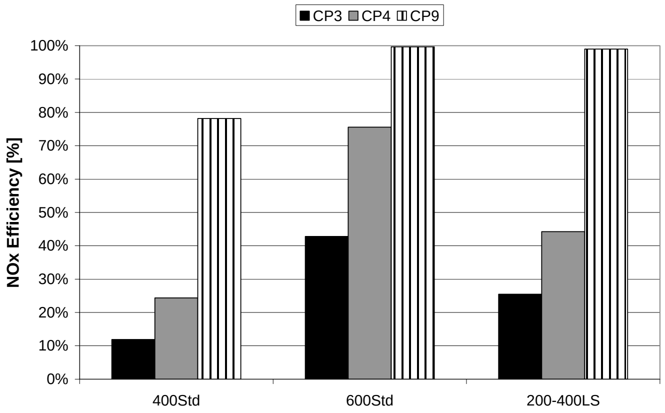

Figure 11. Influence of catalyst structure on NOx conversion efficiency.

WMTC EMISSION RESULTS

After the constant load points test, a set of WMTC test has been carried out. The 400Std has not been measured considering that both 600Std and 200-400LS showed better conversion efficiency in the previous set of tests.

200-400LS catalyst shows remarkable increase of HC and CO catalytical efficiency with respect to 600Std (Figure 12).

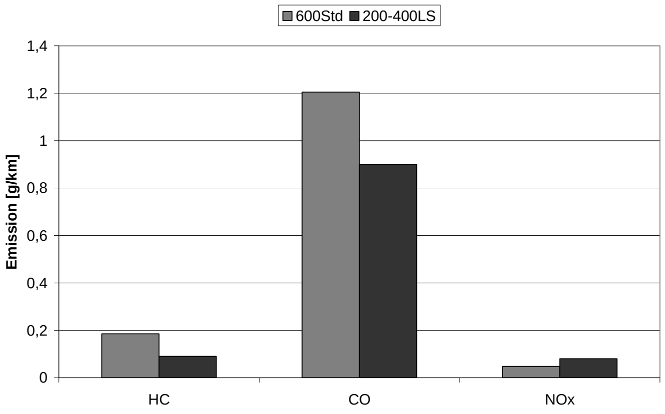

Figure 12. Influence of catalyst structure on conversion efficiency, WMTC.

The reasons for that behavior are the higher thermal mass of the 600Std [Table 3] 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 [9] shows the influence of thermal mass during cold start for standard catalyst.

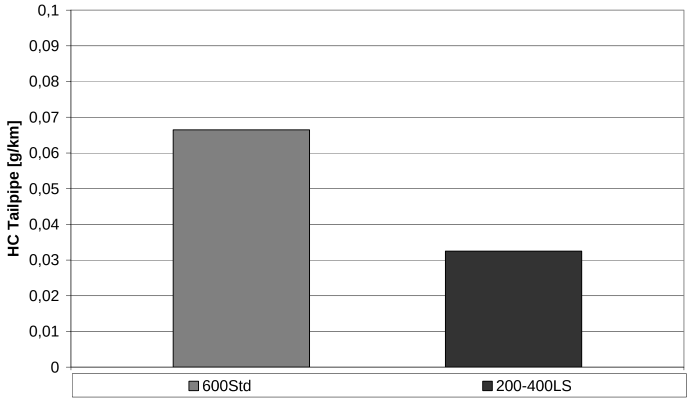

Figure 13. Influence of catalyst structure on HC conversion efficiency during WMTC cold start (first 600 seconds).

Figure 13 shows the HC tailpipe emission during WMTC light off phase of the tested catalysts. It is clear that the major part of the efficiency difference between 600Std and 200-400LS is given in the first 600sec of 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 LS technology 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, the 600Std performs better than 200-400LS (Figure 12). WMTC results confirm the constant load point results and the higher thermal mass of the 600Std doesn’t play a big role.

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

200.400LS substrate has ~45% lower foil material quantity at comparable production costs as the Std technology: the total cost of 200-400LS substrate is then lower than equal volume 600 Standard.

SUMMARY/CONCLUSIONS

Turbulent catalysts present the possibility to reduce the production costs of the exhaust system due to same or better conversion efficiency with same catalyst volume. Higher turbulence in the substrate causes higher exhaust gas stirring, which makes the use of less loading possible. In this way less use of precious metal is possible.

Fist test shows clearly that the two turbulent substrates (TS and LS Technology) with 28% lower PGM amount have better or comparable emission efficiency than a 100cpsi standard technology catalyst with equal volume.

Second test shows that a 200-400LS catalyst has better CO and HC conversion efficiency than a 600 standard catalyst with same volume and PGM loading. 600 Standard catalysts shows on the other hand better NOx conversion efficiency but even the 200-400LS can fulfill a proposed EU4 NOx limit.

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