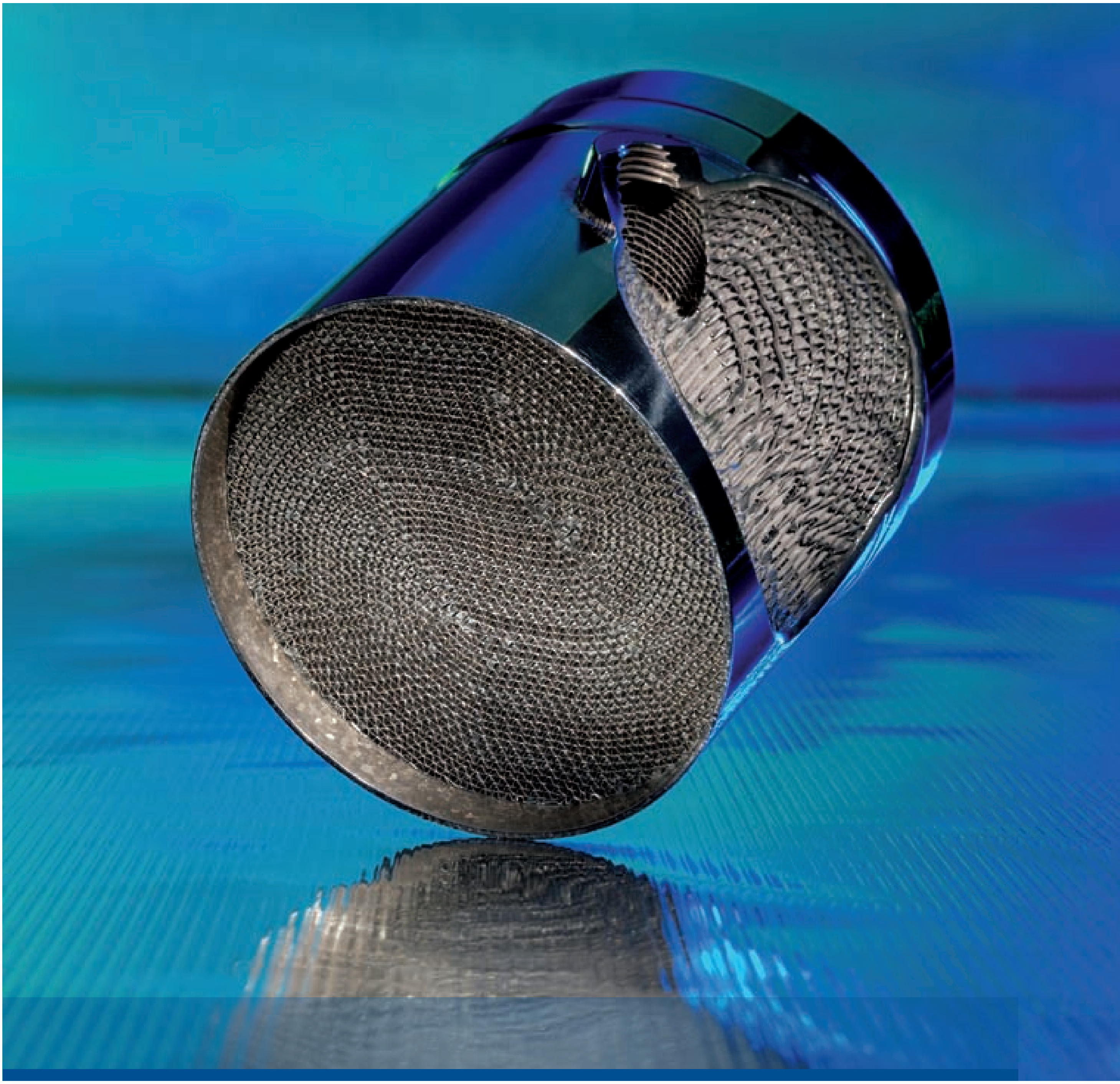

1 Introduction

A controlled and sensible approach towards protecting our environment is something that is subject to changing ideas within society. One thing, however, is clear from observations over the past 25 years: fears that are born of a romanticized desire to protect nature will disappear just like the "dying of forests" caused by acid rain. For this reason, the burning issue of "the CO_2 greenhouse effect" might also undergo a decline in relevance. Diametrically opposed scientific findings could be an indication of the transitory nature of these issues. As was the case with the dying of forests, published majority positions give no clue as to the sustainability of the problem.

By contrast, environmental protection based on healthcare policy has different characteristics. Scientific opinion differs solely with regard to active mechanisms or the degree of harm to health. Experience shows that the mobility industry has taken this on board and, as is clearly evident if we take the aftertreatment of exhaust gases as an example, invariably carried out research in-

Exhaust Aftertreatment between Politics and Technology

The introduction of new exhaust aftertreatment technologies is dependent not only on technical but also on political developments. This overview article written exclusively for MTZ by Wolfgang Maus, CEO of Emitec, presents both the interdependencies and the contradictions between political demands and technical possibilities.

to remedial measures long before it became a public issue. In Europe, insufficient environmental laws allowed legends that the automobile industry had to be forced to introduce catalytic converters or particulate traps to come into existence. It is a fact, however, that achievements of environmental protection have always been realized much faster than originally planned, as has been shown previously by the dramatic reductions achieved in tailpipe emissions.

At the same time, the author recognizes three problems that still remain unsolved in Europe and which are not being tackled seriously enough:

1. Emissions legislation needs to specify a realistic timescale for industrial implementation that will allow the development of new environmental products and corresponding processes. Why, for example, is there still no proposal for EU7, when seven to twelve years may elapse before completely new products are available for series production?

2. Why is there still no so-called "phase-in" or "credits" in Europe, even though experience in the USA teaches us that the automotive industry there is able to translate environmental demands organically into mass production by pioneering measures of technology? Unlike production lines for consumer products, production lines of automotive manufacturers and suppliers cannot be switched overnight.

3. One obvious demand is to call additionally on other aspects of environmental protection as a base of healthcare policy. This is sensible because the automotive industry today ranks as a trailblazer as regards exhaust gas aftertreatment processes. (And this is something that the industry can be proud of!) The deficits identified in points 1. and 2. above only serve to emphasize that a great deal more could be achieved. The success of environmental care by the whole industry would be significantly enhanced if other sectors were to make a more energetic and effective contribution. The result would be not only a more rapid but at the same time a more reasonable and more cost-effective implementation – in the interests of prosperity and optimum viable environmental protection.

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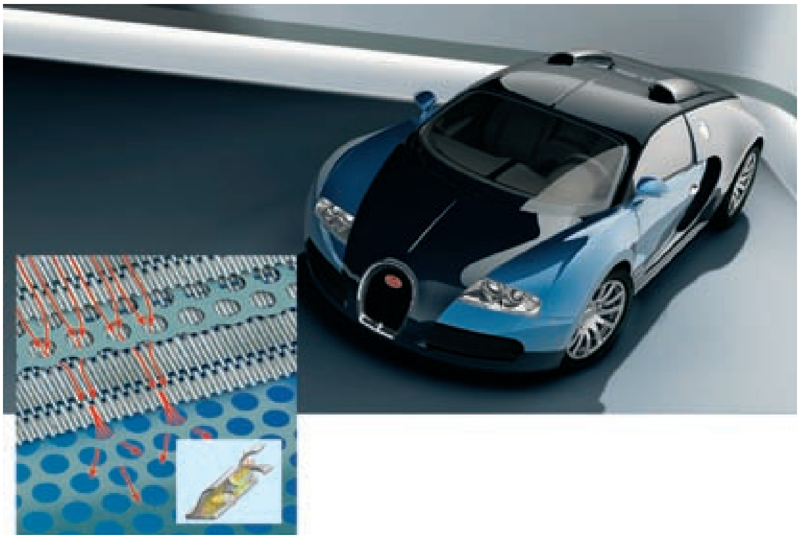

Figure 1: The Bugatti Veyron sports car is fitted with four close-coupled metal catalytic converters with an LS/PE design

Sometimes, making the effort to think outside the box will suffice to put the situation in the right light. According to the EU Workplace Directives and the standards defined in the German regulation "Technische Richtlinie Gefahrstoffe" (TRGS 900, January 2006), the levels of particulate matter in the workplace must not exceed a maximum of 10,000 μg/m³ (respirable fraction, comparable PM 10) or a maximum of 3,000 μg/m³ (comparable PM 2.5). The limit value as far as the ambient air ("immission") is concerned has been defined in an EU Directive since 1 January 2005 as a maximum of 50 μg/m³ of PM 10, something that is clearly below the specified limits of a workplace. This is a maximum daily average that must not be exceeded more than 35 times in any one year.

Thus, a limit value that is, on average, some 100 times higher than this is regarded by the legislators as non-injurious as far as the employee in the workplace is concerned. The latter, who might be an industrial worker, may therefore inhale a quantity of particulate matter during his eight-hour shift, whereas only a few groups of employed people are likely to work on very busy roads for eight hours.

This example, although not wholly comparable, shows that, even though future moves to tighten up even stringent standards may in principle be anticipated, the provision of environmental products is nevertheless becoming a commercial risk due to the unpredictability of political implementation. This is pointed out by examples like the advanced introduction of diesel particulate filters (brought forward by 3 years) and the retrofitting of diesel particulate filters (4 years late)!

Of major significance is the resolute approach adopted by the EU policy makers towards encouraging particle number counting as part of the standards for passenger cars specified by EU6. What is even more important is that we already should have a basis for planning as regards the next tightening up of the EU6 limits. This would enable us to make the specific investments now. Or should we be looking at investing at all while there is no movement on the Workplace Directives front?

As far as nitrogen oxide values are concerned, the situation is quite the same. Since we know for certain that NO_2 as a constituent of NO_x is highly toxic, only 9,500 μg/m³ NO_2 is permitted in the workplace, whereas the current directive dealing with ambient air quality standards (22nd FRG Emissions Control Regulation (BImSchV)) permits a nitrogen dioxide limit of 200 μg/m³ as a 1-hour value (this level may be exceeded 18 times a year) and allows a value of 40 μg/m³ as an average figure for the year. On the basis of the EU5 limit, diesel passenger cars, for example, will still not be immission-neutral. Even Euro 6 diesel passenger vehicles, according to today's knowledge, still would not square the balance sheet.

It is a fact that in the Federal US States of California, Massachusetts, New York, Vermont and Maine, the "Tier2 Bin5" standards that should not exceed NO_x limits equivalent to 8433 μg/m³ are specified. From the point of view of industrial politics, these strict NO_x limits might have been seen as a measure to repel diesel engines but, with the introduction of SCR diesel technology, now tend to be regarded in the USA as a stimulus for environmental innovation.

Those US diesel applications are thus taking over from the spark ignition engine as an environmental benchmark. Whereas, at the beginning of the 1990s, modern SI engines with an electrically heated catalytic converter acquired a reputation for "cleaning up the environment" as far as the oxidizable pollutants HC and CO were concerned, this will soon be an attribute of the diesel passenger vehicle. In 2009, the first US diesels with SCR (selective catalytic reduction) will arrive in Germany – even without the proposed "phase-in", pressure of environmental groups or any incentive by the state to compensate for the obvious competitive disadvantage. The diesel propulsion concept, formerly branded as "dirty", is, with its De-NO_x technologies and particulate filter, turning – at least partially – into an "emissions vacuum cleaner".

That people should adopt a frugal approach to CO_2-emitting energy that promotes our prosperity is also an indisputable maxim. In any case, we are obliged to take care of two commitments. Firstly, for the future we have to leave behind fully developed nuclear power and later fusion energy as a basis of straightforward practical sustainability. Secondly, thanks to our interim successes, we already have it in our hands to further reduce any negative effects on health that the automobile, as a main driver of prosperity, could possibly have. The technology for reducing the exhaust pollutants of motor vehicles that really present problems is already available today; all that is needed is to install this technology in a legal framework and know how to use it on a large industrial scale. Up to now, nobody has been able to seriously accuse the automotive industry of having failed to accelerate the implementation of innovations or to adopt a determined approach to protecting the environment. The following are

Figure 2: PM catalytic converter for truck applications

Figure 3: Metalit NO_x adsorber with structured foils

some examples of already initiated progress and future advancement.

2 Laminar and 'Turbulent' Catalytic Converters

Technology leaps are expected, particularly with regard to converter substrates and particulate filters, because otherwise the system volumes and weights based on traditional components must be increased on a massive scale. Over a period of twenty years, metal substrates have provided the impetus for a change in technology. Initially, alloy foil substrates were developed that featured a low pressure drop and faster catalytic light-off. Metallic honeycomb-based converters were first installed in a close-coupled position to the engine, and the idea of high cell density catalytic converters was born here and, together with leading customers, brought to high-volume production.

Now, the market is confronted with the next technology challenge: after 40 years of laminar heat and chemical mass transfer using honeycomb structures with straight channels, the first motor vehicles featuring more effectively structured and 'turbulent' flow converters are now in commercial production. Even if customized coatings are still at their development stage, publications already confirm the significant improvement potential of what scientific theory claims.

These new types of substrate are also already succeeding in the most powerful 614 kW sports car, **Figure 1**, as in modern common rail high-volume production engines.

The high-volume oxidation, hydrolysis and SCR catalytic converters in HDVs and off-road applications are particularly suitable for the new developments. The metal converters made from corrugated foils featuring a longitudinal structure (LS) generate a turbulent flow profile that effectively promotes the chemical conversion on an active catalytic coating. One part of the catalytically coated cell wall is located in the midst of the channel flow. Instead of standard oxidation converters, this ensures greater conversion and allows reduced catalytic converter volumes. This enables cost savings to be achieved in particular as far as precious metals are concerned. Despite a volume reduction of at least a quarter, these new, turbulent flow substrates are as efficient as conventional oxidation catalytic converters with laminar flow.

3 Progress in Soot Particle Reduction

Nowadays in Germany, diesel passenger vehicles are predominantly fitted as standard with ceramic wall-flow particle filters that store soot and, in most cases, burn it off by additionally injected fuel after detecting the increase in pressure drop above a certain limit. In order to achieve a filtration effect in excess of 90 %, the filter cake needs to be built up in such a way that even very fine particulate matter can be efficiently trapped by this filtration layer structure.

Back in 2004, MAN introduced into series production a new type of metal partial flow particulate filter for trucks with the brand name PM-Kat® (PM: particulate matter), **Figure 2**. Like the ceramic version, this new metallic bypass filter works on the deep bed filtration principle. In contrast to the ceramic wall flow type, this filter (which is also called PM-Metalit®) consists of steel foils with guide vanes that channel a partial flow of exhaust gases over a very thin steel wire fleece that traps the particles by adhesion. Several filter stages act in series to filter the soot from the exhaust. Continuous particle reduction is achieved by means of the CRT process, in which the soot is oxidized by oxygen provided by the NO_2 generated by the engine and the upstream oxidation catalytic converter. Studies have shown that this partial-flow trapping and the CRT process allow efficiencies of 80 to 90 % to be achieved. It is particularly designed for the reduction of so-called nanoparticles. As regards visible particulates from older engines, the PM weight reductions that can be achieved for passenger cars are between 30 and 50 % and, for HDVs, between 60 and 80 %. The continuous and therefore blocking-free operating mode has resulted in PM-Metalit becoming the preferred retro-fitting concept.

From today's modern diesel engines, it may be anticipated that further improvements in diesel engine combustion will increasingly avoid "heavy" visible particles larger than approximately 400 nm, which is to a large extent already the case in modern HDVs. This highlights the opportunity of new dedicated ultra fine soot trapping applications, including also those in combination with SCR.

Figure 4: New, turbulent PT pre-turbocharger, Metalit and oxidation catalytic converters

4 NO_x Adsorbers

As already mentioned, the important issue in the future as far as diesel and lean burn SI engines are concerned will be the reduction of nitrogen oxides. SCR technology has been introduced in HDVs and reduces the nitrogen oxides with the aid of the ammonia formed by injecting urea into the exhaust system in the downstream catalytic converter. The CO_2 and global warming debate has given new impetus to the leaner, less fuel consuming SI engine, which will also require de-NO_xing due to higher NO_x engine-out emissions. In the meantime and as an alternative to the SCR process, NO_x adsorbers, also known as lean NO_x trap converters (LNT), have been used in series production and are especially suitable for smaller and medium-sized passenger cars. Their performance in diesels and lean SI engines has nevertheless not been satisfactory so far. One has to take into account the fact that development is still in an early stage. This particularly relates to the utilizable temperature range and stability at high temperatures.

In Japan, this challenge has been addressed through ambitious cooperative industrial research projects, based on which some surprising results have, on occasions, been presented at EU congresses. Other studies show incomplete solutions of the problems of efficiency, ageing and the excessive use of precious metals as well as costs. This means that completely new approaches and organic improvements are required. According to Japanese sources, NO_x adsorbers using coatings based on potassium materials that feature significantly increased NO_x conversion rates and improved ageing can be produced. Using metal foils with a „turbulent" flow profile, **Figure 3**, they are also a very interesting alternative to the SCR process applied to engines with larger displacements. Further potential is offered by integrated lambda sensors which, when mounted in the rear section of the exhaust system, will detect unwanted NO_x breakthrough at an early stage, and additionally supply information relating to ageing (see Section 7).

Due to the special coating, the NO_x adsorber initially stores the nitrogen oxides until all the capacity is used, subsequently reducing them during a short regeneration phase with additional fuel and converting them to the nitrogen present in the ambient air. This endothermic process takes place unnoticed by the driver and ensures that the NO_x adsorber removes more than 70 % of the NO_x in normal vehicle operation. In the future, however, in order to comply with the strict Euro 5 limits, more frequent NO_x adsorber regeneration will be necessary, and this will result in increased fuel consumption. Another issue relates to the sensitivity of the coating to sulphur, which makes the use of adsorber technology in many countries practically impossible. Even with almost sulphur-free fuels, de-sulphurization cycles are unavoidable.

NO_x adsorbers are already being used as standard in SI and diesel engines. The high level of the precious metal platinum needed for the NO_x adsorber coating could impose limits on extended usage if the market prices continue to rise.

5 High-performance SCR Systems

Strict limits on exhaust gases in the future, such as US 2010 or EU6, have been responsible over the last ten years for the fact that SCR (selective catalytic reduction) – in particular for diesel engines with larger displacements – has received increasing attention worldwide. European HDV manufacturers are demonstrating series functionality in everyday ope-

Figure 5: Electrically heated catalyst

ration. An integral component of any SCR system is an upstream oxidation catalytic converter that oxidizes CO and HC and generates NO_2. In view of the fact that NO_x and soot emissions will be subject to even stricter limits in the future, a combination of series soot filters with SCR is an obvious solution. The standard SCRT process, which is licensed by Daimler, features a particulate filter (DPF) downstream of the oxidation catalytic converter that is capable of eliminating a proportion of the soot particles accumulated with the help of the NO_2 and in accordance with the above-mentioned CRT process. The remaining soot is stored until it is burnt in an active regeneration. Downstream of the DPF, the aqueous solution of urea is injected and is sprayed into the exhaust gas using a mixer and converted to ammonia (NH_3) on the following hydrolysis catalyst. This process consumes heat from the exhaust gas and therefore requires a homogeneous distribution of all species. It could be demonstrated that a perfect distribution of urea and an almost 100 % decomposition to ammonia is optimally supported by using substrates with coarse-cell mixing design (MX) and perforated design (PE), which provide a radial gas exchange. This process is supported by a hydrolysis coating to prevent the formation of by-products that cause blockages The NH_3 is capable of reducing the NO_x to nitrogen via the SCR catalytic converter. At the SCR reduction stages, the LS profile enables a more complete chemical conversion on the active surface as a result of improved mass transfer. The perforated flat foils (PE) actively assist this process, ensuring that here too there is a balance of concentrations between the individual flow channels in the substrate.

A further clean-up catalytic converter can be attached where necessary to prevent NH_3 emission. Costly engine-related measures such as high-pressure fuel injection, multi-stage supercharging and high-grade EGR (exhaust gas recirculation), which significantly reduce engine-out NO_x emissions, keep urea consumption within viable limits. The overall expense is however considerable. Accordingly, the next challenge is how to achieve a considerable reduction in system costs.

In large-scale production and millions of miles of useful life, the series diesel particulate filter module, Metalit oxi-cat plus PM Metalit, can now be combined by connecting a second module, the SCR catalytic converter, to form a compact and innovative SCRi® system. Urea is injected upstream of the bypass flow particulate filter, which has a hydrolysis coating and thus achieves a dual function of particle reduction and ammonia generation. The SCR-NO_x reduction stage then follows. The two-module concept is called SCRi® (= SCR integrated) and, due to the continuous operation implemented here for the first time, represents a simpler to control, compact and cost-effective combination of series production components. The avoidance of regeneration intervals, which are unavoidable with wall-flow filters, eliminates the need to increase the exhaust gas temperature to more than 500°C, and this means that the downstream SCR converters are not subjected to excessive thermal loads. The SCRi system also features the additional benefit of a lower pressure drop.

6 Close-coupled or Electrically Heated Catalytic Converters

Cold engine starts up to the point where the chemical reactions in catalytic converter systems are activated are becoming increasingly important as passenger car diesel exhaust gases become cooler. For commercial or HDV vehicles, the future WHTC (worldwide harmonized transient cycle) is set to present a new challenge. In the future, therefore, increasing effort will be needed to limit the cold start emissions of dynamic test cycles. However, this also applies for LDVs and HDVs during continuous operation when the engine (and as a result the exhaust gases) is cooling down, for example during overrun operation, when the working temperature of the aftertreatment is not achieved.

The pre-turbocharger catalytic converter, **Figure 4**, will be a solution for the critical sections of those test conditions and, in addition, also represents a significant cost reduction measure due to its turbulent flow regime. Over 20,000 "E-cats" have been successfully applied in twelve-cylinder SI engines, **Figure 5**, paving the way for the SULEV conformity of these engines. When it comes to the diesel engine, new importance can be anticipated. In addition to extremely fast start-up, it prevents undue cooling of the catalytic converter in continuous operation in low-load and deceleration phases.

7 Future Developments

Catalytic converters in a close-coupled position are state-of-the-art technology as this position promotes rapid catalytic light-off. Further significant improvements can be achieved using the compact catalytic converter, which is about to be launched in series production. This is a single "brick" or cascade metal converter (2 bricks). The purified gas flows in a

Figure 6: Enhanced performance with low installation space: lambda sensor catalytic converter with a PE design

Figure 7: Lambda sensor catalytic converter for improved lambda and cold start control

counter-direction in a surrounding gap. The gas inlet and outlet are therefore located on the same side. This saves space and minimizes the amount of mass to be heated up and heat inertia can be utilized during cooling down, which will be of critical importance for both SI and diesel engines in future. Primarily for those applications in which the catalytic converter needs to be flange-mounted directly on the turbocharger, the compact catalytic converter represents an ideal and cost-effective design.

State-of-the-art catalytic converters are monitored by a number of lambda (oxygen) and temperature sensors. In the future, it is anticipated that further sensors will be added to these, for example for the measurement of nitrogen oxides and hydrocarbons. In addition, wherever systems are close-coupled to the engine, the installation of the sensors frequently poses a problem due to space constraints.

Catalytic converters featuring an integrated lambda sensor, **Figure 6**, are already successful in series production. The position within the substrate protects the lambda sensor against condensed water, **Figure 7**, because any humidity will be absorbed by the coating and then evaporated. As a result of this protection, the lambda sensor can immediately be heated after an engine start and therefore has the ability to control the air/fuel ratio to an optimum in the shortest possible time. This offers the opportunity to reduce cold start emissions considerably. In the case of ceramics, recesses are milled into the front faces of the honeycomb structures and arranged in such a way as to create the necessary opening. Holes are also drilled into the brick and these must be at a safe clearance from the front faces.

The construction of the metallic counterpart consists of the mantle carrying the flange to mount the sensor. The cavern is pre-manufactured by holes stamped into the foil. Winding-up the matrix foils to a S-shape design forms the space for the sensor. These may be located close to the front faces, and more than one can easily be applied. In the case of the PE design in particular (the corrugated and flat foils of the substrate are perforated), the exhaust gas is mixed more thoroughly within the catalytic converter, so that individual cylinder-related effects, for example, which produce uneven lambda sensor signals are significantly reduced. As a result of these effects, costs can be reduced.

8 Summary

The optimal interplay over time between environmental regulations and the introduction of new technologies in all sectors of emissions and immissions will generate markets for further innovations. This supports the need for stronger environmental protection in the light of a worldwide growth in individual mobility. A direct influence on the competitiveness of vehicle manufacturers and suppliers can be observed. Faster improvements and ambitious results could be achieved if longer-term environmental targets could be set in order to stimulate investment.

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