Ultra-Low Power Electrically-Heated Catalyst System

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1. Introduction

Compliance with future emission standards in the United States of America, California in particular, and in Europe, will require catalytic converter modifications to achieve increased effectiveness of emission treatment. A significant factor is cold start behaviour. At least one part of the catalytic converter must be catalytically active shortly following start of the engine - about 15 seconds in the FTP (Federal Test Procedure) test, i.e. achieve operating temperature in this frame - in order to attain ULEV values [1]. As has frequently been indicated in the past, the heated catalytic converter is one possible solution for achieving future standard values [2, 3, 4]. In the course of development, modifications to heated catalytic converter and exhaust systems, as well as engine management, have successfully lowered energy consumption by post-heating to between 1.5 and 2 kW [5, 6]. It can be seen from Figure 1 that numerous applications of various heated catalytic converters successfully achieve the target area HC < ULEV values at a heating energy of < 30 Wh.

Fig. 1: FTP results versus power demand of various heated catalytic converter applications.
These achievements notwithstanding, the development of heated catalytic converter systems can in no way be considered completed. Durability, and the provision of required electrical energy with vehicle electric systems, are not yet totally proven. The purpose of this study is to provide the necessary proof with the aid of comprehensive durability testing and the application of a heated catalytic converter in a Porsche 968. Within the scope of these tests, the new generation „Series 6“ Emitec heated catalytic converters were implemented.

1. **Heated Catalytic Converter Series 6**

The heated catalytic converter Series 6 is a unit comprising a heated part and an unheated part, the supporting catalytic converter.

The supporting part is mechanically connected to the heated part by brazed, electrically insulated supporting pins. Both catalysts are manufactured in the proven Emitec-S-Design (Fig. 2).

![Heated catalytic converter Series 6](image)

**Fig. 2: Heated catalytic converter Series 6**

The electrical resistance of a heated catalytic converter is determined by the cross section, the length of the conductor and the specific electrical resistance of the foil material. The conductor cross section is determined by the number, thickness and width (converter length) of the parallel-connected layers of foils. The thickness of this package and the cross section of the catalytic converter determine the length of the conductor. The specific electrical resistance depends on the material, and stands at 1.37 Ω mm²/m for the aluminium chrome heat-conduction alloy typically employed in the construction of metal catalytic converters. Through variation of the individual influential factors, the Series 6 catalytic converter can be designed to achieve electrical resistance between 0.25 and 0.06 ohms (50A - 200A/12V) [7]. A conductor package so constructed is rolled into a S-form, whereby electrical insulation is ensured by an air gap.

The air gap guarantees wear-free insulation even under conditions of increased vibration. Contact within the layered package takes place over two opposing enclosure shells via two sealed ducts. The structure of the heated catalytic converter provides for full electrical insulation to the supporting part and thus to the exhaust system.

Mechanical stability is ensured by means of numerous pins brazed into the heated structure as well as the supporting catalyst. The number and distribution of these pins is determined by the length of the package and the maximum permissible tension at operating temperature and an acceleration rate of 60 g.

The construction allows relatively free layout of the heated catalyst with regard to electrical resistance, without influencing the mechanical stability, this mainly being provided by the supporting catalyst.

This in turn allows the realization of heated catalysts of diameters varying from Ø 60 to Ø 127 mm. The objective of the development was the representation of a heated catalyst with the smallest possible mass and the greatest possible catalytic surface [1]. The following offers a closer examination of 3 sizes of heated catalyst Serie 6:

<table>
<thead>
<tr>
<th>Heated Catalyst Series 6</th>
<th>Catalyst diameter (mm)</th>
<th>Catalyst length (mm)</th>
<th>Cell density (cpp)</th>
<th>Amperage at 12 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 90 x 10/50.8 mm</td>
<td>90/90</td>
<td>10/50.8</td>
<td>200/400</td>
<td>50 A</td>
</tr>
<tr>
<td>Ø 90 x 11/50.8 mm</td>
<td>90/90</td>
<td>11/50.8</td>
<td>160/400</td>
<td>150 A</td>
</tr>
<tr>
<td>Ø 70 x 10/50.8 mm</td>
<td>70/70</td>
<td>10/50.8</td>
<td>300/400</td>
<td>100 A</td>
</tr>
</tbody>
</table>

**Table 1:**

Figure 3 shows the heating-up behaviour of the individual catalysts in still air.

![Temperature Gradient](image)

**Fig. 3: Heating-up behaviour of Series 6 heated catalysts**
2. Durability Testing

For proof of durability, the heated catalytic converters must be subjected to the following standard tests:
- Vibration Test
- Inner Thermal Cycling Test (ITC)
- Hot Shake Test (HST)
- Outer Thermal Cycling Test (OTC)
- Engine Thermal Cycling Test (ETC)
- Electrical Inner Thermal Cycling Test (EITC)
- Vehicle Durability Test

2.1 Vibration Test

The resonance frequency of a catalytic converter must lie in an area above the critical vibrations occurring in the vehicle. With the aid of the vibration test the resonance frequencies of the test catalysts are established on a 70 kN electric shaker in three axes.

The following values were determined for heated catalytic converters of the series 6 type:

<table>
<thead>
<tr>
<th></th>
<th>x Axis</th>
<th>y Axis</th>
<th>z Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 90, 50 A</td>
<td>695 Hz</td>
<td>670 Hz</td>
<td>720 Hz</td>
</tr>
<tr>
<td>Ø 90, 150 A</td>
<td>735 Hz</td>
<td>730 Hz</td>
<td>No Resonance</td>
</tr>
</tbody>
</table>

During actual vehicle operation, in a transverse-mounted inline four-cylinder engine with the heated catalyst in the suggested position, the vibration stress indicated in Figure 4 occurs at an engine speed of 5400 - 5800 rpm.

It can be recognized that at frequencies above 450 Hz practically no further excitation energy is present. This would indicate that the vibration load in this application can be considered noncritical for the heated catalysts under consideration.

2.2 Exhaust Emission Simulator Tests

The following tests are carried out on an exhaust emission simulator with an attached heat exchanger.

Table 2: Exhaust gas simulator technical data

| Governing: | Closed-loop control with lambda sensor |
| Maximum effective power output: | 120 kW |
| Air/fuel ratio (lambda): | 0.9 - 1.2 |
| Fuel type: | Unleaded 98 octane RON |
| Exhaust gas temperature: | 100 °C - 1300 °C |
| max. deviation ± 20 °C |
| Max. exhaust gas flow rate: | 160 kg/h ± 2.5 kg/h |

2.2.1 Inner Thermal Cycling Test (ITC)

Widely varying operating conditions during actual operation lead to differences in temperature between the catalyst mantle and the catalyst matrix. This causes different elongations which can result in deformation of the matrix. During the ITC test the catalyst is heated to 900 °C at a rate of 1500 K/min. After a 7.5-minute period at this temperature, the converter is cooled from the exterior to 300°C without gas flow over a cooling phase lasting 7.5 minutes. Altogether a total of 500 such cycles is carried out (Fig. 5) to determine the maximum deformation.

![Fig. 4: Vibration stress to a catalytic converter in the vehicle](image)

![Fig. 5: ITC Test](image)
2.2.2 Hot Shake Test (HST)

To simulate axial vibration stress at extreme operating temperatures, the catalysts are heated to 900 °C then vibrated at an acceleration rate of 40 g and a frequency of 80 Hz for 100 hours. The sinusoidal excitation is effected by an electrically driven eccentric shaft.

2.2.3 Outer Thermal Cycling Test (OTC)

This test is performed to show the effect of splashwater on the hot catalytic converter such as occurs when the vehicle is driven through water. Exhaust gas heated to 900 °C flows through the test object. After a heating up period of 5 minutes, 2 liters of water are sprayed onto the catalytic converter within 30 s through three jets. The test is based on 150 such cycles (see Fig. 6).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Temperature</td>
<td>Te = 900°C</td>
</tr>
<tr>
<td>Mass Flow</td>
<td>m = 160 kg/h</td>
</tr>
<tr>
<td>Air/Fuel Ratio</td>
<td>λ = 1.0</td>
</tr>
<tr>
<td>Time for Stabilizing</td>
<td>ts = 30 min</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>t = 5.5 min</td>
</tr>
<tr>
<td>Time for Heating Up</td>
<td>th = 5.0 min</td>
</tr>
<tr>
<td>Time for Water Spraying</td>
<td>tw = 0.5 min</td>
</tr>
<tr>
<td>Water Pressure</td>
<td>PW = 1.75 bar</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>TW = &lt; 20°C</td>
</tr>
<tr>
<td>Water Flow</td>
<td>W = 2 l</td>
</tr>
<tr>
<td>Number of Cycles</td>
<td>N = 150</td>
</tr>
</tbody>
</table>

![OTC Test Diagram](image)

![Graph: Engine Temperature vs Time](image)

Fig. 6: OTC Test

Following all these tests, the functionality of the heated catalytic converters tested was found to be unimpaired.

2.3 Engine Thermal Cycling Test (ETC)

Following the successful conclusion of the exhaust emission simulator tests, the catalysts were tested on the engine test bench, whereby they were subjected to a combination of ITC and HST. The Emitec Standard Test Program comprises a 420 second heating phase and a - 480 s cooling phase with the engine switched off. During the heating phase, speeds of up to 5500 rpm are reached at a catalyst gas inlet temperature of 850 °C (see Fig. 7).

![Graph: Engine Speed vs Time](image)

This test consists of more than 800 cycles. At the end, the Series 6 heated catalytic converter Ø 90 x 10/50.8, 100 A, was fully functional both electrically and mechanically.

2.4 Electrical Inner Thermal Cycling Test (EITC)

To simulate the heating-up behaviour of the catalytic converter, the heated part is heated electrically to 500 °C and subsequently cooled down to 50 °C with a cool-air fan. Heating as well as cooling times vary for the individual versions depending on amperage and size of catalyst. The entire test procedure per catalytic converter takes 50,000 cycles, whereby the catalyst is particularly stressed by the differences in thermal elongations between the heated and supporting parts. Because of the free elongation compensation made possible by the air gap insulation, the tested catalysts were found to be quite undamaged following this test.
2.5 Vehicle Durability Test

The test vehicles include a 2-liter, 4-cylinder, 85 kW VW-Passat and a 5-cylinder, 103 kW Volvo 850. While the Volvo is operated as a taxi, the Passat is completing a 440 km round trip as a test vehicle. Efforts were made to maintain relatively consistent driving behaviour during each round trip, depending on traffic conditions.

The test circuit for the Passat comprises

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Max Velocity (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70% Highways</td>
<td>200 km/h</td>
</tr>
<tr>
<td>20% Rural roads</td>
<td>100 km/h</td>
</tr>
<tr>
<td>10% Urban roads</td>
<td>50 km/h</td>
</tr>
</tbody>
</table>

The distributions of velocity and inlet temperature are represented in Figure 8.

![Graph showing velocity and inlet temperature distributions](image)

Fig. 8: Velocity and inlet temperature distributions in the test vehicle.

By January 1994, a Series 6 heated catalyst, Ø 90, 100 A will have been operating in the Passat over a distance of 70,000 km and a Series 6 catalyst, Ø 70, 100 A in the Volvo over 30,000 km. The plan is to test both versions further to a total distance of 160,000 km.

3. Application to the Porsche 968

The study is based on developments on the Porsche 968 (3-liter, 4-cylinder 4-valve engine) presented in SAE Paper 930384, with the following objectives:

- Increased exhaust emission treatment efficiency
- Substantiation of adequacy of electrical supply from vehicle electric systems

3.1. Test set-up and procedure

To achieve the above objectives, the following strategies were implemented:

a) Modification of engine management parameters

To expedite faster heating-up of the catalytic converter after engine cranking, the following modifications to the warm-up parameters were carried out:

- increased idle speed
- increased air-mass flow during idling
- retarded spark timing
- reduced warmup enrichment
- reduced acceleration enrichment

b) Reduction in heat losses of the exhaust gas in front of the catalyst

To reduce heat losses from exhaust gas flowing to the catalyst, the thermal mass in front of the catalyst was reduced.

With the implementation of a 4-in-1 exhaust manifold with a wall thickness of 1.5 mm and a single pipe in front of the catalyst, a weight reduction of 30% could be achieved. The exhaust system with temperature measurement points is represented in Figure 9.

![Exhaust gas system with temperature measurement points](image)

Fig. 9: Exhaust gas system with temperature measurement points

c) Optimization of secondary air injection

For optimal secondary air injection, a 10 mm pipe was inserted into each exhaust channel and positioned centrally versus the exhaust flow. The transverse section of these pipes was sealed, and the circumference provided
with three radial openings; these openings serve to provide an optimal mixture of air and exhaust gas. The targeted air/fuel ratio of 15.4/1 (lambda = 1.05) during the first 40-60 seconds following cold start of engine was maintained by means of an rpm-dependent secondary airflow.

d) Implementation of a Series 6 heated catalytic converter and optimization of catalyst volume and position

During the final stages of development the following metal catalytic converter system was implemented:

Table 3:

<table>
<thead>
<tr>
<th>Size</th>
<th>Cell-density</th>
<th>Volume</th>
<th>Coating</th>
<th>Amperage at 12 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heated catalyst</td>
<td>Ø 90 x 10/50.8 mm</td>
<td>200/400 cpsi</td>
<td>0.39 l</td>
<td>50 g/ft²</td>
</tr>
<tr>
<td>Main catalyst</td>
<td>Ø 127 x 120 mm</td>
<td>300 TS</td>
<td>1.52 l</td>
<td>50 g/ft²</td>
</tr>
</tbody>
</table>

The catalytic volume of the heated part, with integrated supporting catalytic converter, amounts to 20 % of the total volume. The catalyst system in cascade formation was situated about 450 mm behind the manifold flange. In this position, the main catalyst is situated ~ 340 mm closer to the engine than the production catalyst. Parallel to this, the volume of the main catalyst was reduced by 38 %.

To achieve optimal control of the fuel/air ratio, a heated (11 W) λ-sensor was positioned approximately 100 mm in front of the heated catalyst.

e) Implementation of an optimized alternator

The 115 A production alternator was replaced by a slightly more efficient alternator with an optimized current delivery at low engine speeds (see chapter 4.).

Using this configuration, the FTP tests were carried out on a chassis dynamometer at the Porsche environmental protection test centre. In addition to exhaust gas emissions, exhaust gas temperatures and engine management data, vehicle electrical systems amperages and voltages were also measured during the FTP tests.

3.2 Exhaust gas test results - numerical simulation

To estimate the exhaust gas temperature and light-off behaviour of the heated catalytic converter system with a heating power of approximately 1200 watts, computations were made with the aid of a Finite Elemente program for calculation of transient conditions. Input data consisted of exhaust gas temperatures in front of the catalyst, exhaust gas mass flow and raw emissions from the test vehicle (Figure 10).

This numerical simulation establishes that with a heating power of 1200 watts, light-off times of ~12 sec can be achieved. Assuming satisfactory results from test bags 2 and 3, the accumulated HC values after 100 sec allow results lower than ULEV.

This computation was based on a heating-up period of 20 seconds.

3.3 Exhaust gas test results - chassis dynamometer

In order to get different gastemperatures in front of the heated catalyst the tests were done with the production and a modified (chapter 3.1) engine manage-
ment configuration. This resulted in a 40-50 K lower gas-
temperature using the production version 20s following
cold start (Figure 12 b).

Under these conditions, utilizing an unheated catalyst,
the catalyst structure temperature is ~ 50 - 60 K lower
(figure 12 a,12 b) This should simulate higher light-off
temperatures of an aged catalyst.

Since the light-off temperatures of fresh catalysts lie
well below 300 °C, an initial exothermic reaction in the
catalyst takes place approximately 15 - 20 seconds after
starting the engine. This allows only minimal scope for
further improvements to the catalyst light-off behaviour
using additional electrical heating methods.

Fig. 12 a: Gas- and structure temperature curves showing the first 60
seconds of the FTP cycle with modified engine management
configuration

FTP-results with modified engine management con-
figuration:
The FTP results from measurements on the exhaust
gas dynamometer indicate that even without heating
up the catalyst, using the methods described in 3.1 and
fresh catalysts, values below ULEV can be achieved
(Table 4, Figure 13, 14). This is a result of the fast rise in
the exhaust gas temperature in front of the catalyst to
over 300 °C (Figure 12) following a 20 sec idling phase.

Fig. 12 b: Gas- and structure temperature curves showing the first 60
seconds of the FTP cycle with production engine manage-
ment configuration

FTP-results with production engine management
configuration:
The HC-emissions lies significantly above the ULEV
standard (table 4). Therefore in order to comply with
ULEV standards with aged catalysts, the electrically
heated catalyst must be utilized. This causes a rise of
approximately 70 K in the monolith behind the heated
catalyst 20 s following engine cranking, and compens-
sates for the age-related increase in the light-off
temperature. This can be achieved with a relatively
low additional electrical heating energy with 70 - 100 A
current input (see also computations).
catalysts with a low electrical consumption can certainly be supplied by the vehicle battery without endangering its life – A condition being that the battery will be recharged even during a short run and/or under unfavorable vehicle systems conditions. Since this cannot be completely relied upon particularly during cold weather, a larger battery would probably be required to bridge these contingencies.

The supply to the electrically heated catalyst by the alternator alone is beneficial – In that during the heating-up phase, the alternator is still cold and approximately 30% more efficient than at operating temperature (Fig. 15). If the power output of the alternator is sufficient to supply the electrically heated catalyst, the need for a larger vehicle battery becomes redundant.

As mentioned in 3.1., an alternator capable of providing stronger current at lower revolutions than the production alternator was installed in the test vehicle (Fig. 15).

By installing voltage and current measuring points at various locations in the vehicle electrical system and the heated converter it was possible to obtain an electrical energy balance.

Significant results emerging from the measurements in the FTP test are:
- the heated catalytic converter is almost completely provided with power from the alternator
- the charging balance is restored in less than 100 s after testing begins, charge factor 1, (Fig. 16, 17, 18).

The following illustrations represent voltages and currents during the cold start phase of the FTP cycle.
Measurement of the currents (Fig. 17) establish that it is quite feasible for at least heated catalysts with a lower current consumption to be supplied almost completely by the alternator. This possibility would benefit from a vehicle systems management strategy capable of excluding other, larger loads such as the rear window defogger or seat heating during the few seconds of the heating-up period of the catalyst.

Where the supply to the electrically heated catalyst is derived from both battery and alternator, the alternator power input and therefore the engine loads are increased immediately following cranking. At a nominal electrical power output of 1200 watts, a mechanical drive power of ~ 2 kW must be achieved during engine idling. The resulting higher exhaust gas mass flow - initially unfavorable for the exhaust gas emission - can, on the other hand, have a positive effect on the heating of the catalyst, whereby an increase in pollutant emission is not expected.

5. Summary

In order to improve the effectiveness of exhaust gas treatment systems, a new generation of Series 6 heated catalytic converters will be presented, which is characterized by

- an increased heating power spectrum with a current input of between 50 and 300 A,
- minimal mass to promote extremely brief heating times,
- fulfillment of all electrical and mechanical durability requirements.

The application of a lower power consumption heated catalyst in a Porsche 968 indicates that

- through supporting measures such as adaptation of engine management strategy in the warming-up phase, reduction of the exhaust system mass to be heated, catalyst position close to the engine and optimization of the secondary air injection, the effectiveness to the exhaust gas treatment will improve to the extent that with fresh catalysts the ULEV values can be maintained.
- to comply with the ULEV values with aged catalysts, the implementation of heated systems will be necessary to ensure long term effectiveness, particularly where gas temperature and raw emission are unfavorable, compared to in the Porsche 968.
- the implementation of heated catalysts with a heating power > 1000 watts will only effect a small reduction in emission
- the generator alone can provide sufficient power to supply low-power heated catalysts
- a larger battery becomes unnecessary.
6. Conclusions

The emission data established for the Porsche 968 indicate that with a heated catalytic converter with relatively low heating current, ULEV values can be achieved. Where heating current is not higher than 100 - 150 A, the total EHC-system costs can be reduced by using the production car battery and by the use of a simple power circuit-breaker (relay).

The cross-section of heating current cables - and thus their weight - is decreased significantly, when compared with the requirements for a heating current of 300 - 400 A customary until now.

Further developmental work must include exhaust gas analysis using aged catalysts to determine the stability of emission levels. With regard to other applications, particularly large-volume V-engines, the extent to which the measures described are sufficient to achieve ULEV values with heating powers of 1000 - 2000 Watt remains to be determined. For the Series 6 heated catalyst, however, a reliable unit with a low energy consumption is available. Research is currently being carried out on converters in which the heated and main catalysts are constructed as a single unit, with regard to emissions and OBD requirements.

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