Improved Cell Design for Increased Catalytic Conversion Efficiency

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Introduction

Compliance with future emission standards in the United States of America and Europe will require modifications to increase the effectiveness of catalytic converters. A significant factor in this respect is not only the conversion in the cold start phase, but also improvement of conversion at vehicle operating temperatures [1]. For example, in order to achieve ULEV values in compliance with Californian emission standards at an assumed raw engine out emission of 2.0 HC g/m, a conversion rate of 98 % in the overall testing is imperative [2]. Parallel to reduced emissions legislation will also require a lower specific fuel consumption [3]. The loss of engine power from increased exhaust gas back pressure in addition to larger space requirement for a catalytic converter in the engine compartment resulting from such measures are of critical importance.

With the aid of a special method of structuring the channels, the so-called transversal structure (TS), it is possible to increase the effectiveness of the catalyst by increasing the transverse flow of the gas in the channels. The paper will demonstrate that by reducing the cell density, the increased pressure resulting from the TS design can be compensated for or even overcompensated by a simultaneous increase in effectiveness. The reduced heat capacity of the matrix structure demonstrated in this variant improves the light-off behaviour of the catalytic converter. The TS design also presents the possibility of reducing the catalyst volume for applications with restricted space allowances whilst retaining identical effectiveness.
1. Influence of Channel Structure on Flow in Metal Catalytic Converters

The object is to increase effectiveness within the catalyst by producing turbulence, or at least radial flow direction components. This increases the radial transportation velocity of the mass (emissions) through the channels to the walls, which with strict laminar flow would otherwise be effected by diffusion. The metal catalytic converter offers a variety of constructive possibilities for the channel structure, such as:

a) SM technique  
b) LS technique  
c) Perforation of foil  
d) Diversion and separation moulding

In the past, a number of techniques have been presented, as for example the SM technique [4]. This technique involved splitting the flow in the catalyst channel to effect multiple repetitions of the turbulent intake flow. With the LS structure, this repetitive intake flow is achieved with partial counter-corrugation of the corrugated layers in the catalyst (Fig. 1).

This technique increases catalytic effectiveness significantly in conjunction with a simultaneous increase in loss of pressure. Depending on the construction the cell density is limited to 100 - 200 cpsl. As a result of the reduction in geometrical surface - compared with that of 400 cpsl catalysts - the emission stability in a converter in an aged condition is reduced, particularly in the conversion of nitrogen oxide [5].

Using the SM technique, by elimination of the smooth layer usually inserted between the corrugated layers in metal catalyst supports (SQ), a homogeneous distribution of flow through the catalyst cross section can also be achieved. The motivating force is created by differences in pressure losses in the channel, a result of both irregular flow distribution and thus flow velocity through the channels. This difference in pressure in the channel can be equalized in a radial direction via the openings in the channels.

A homogeneous flow in the catalyst can also be effected by perforations in the foils. This, however, leads to a reduction of the geometric surface without creating an appreciable improvement in the mass transfer.

One alternative is the formation of diversion and separation profiles, which involves partially punching out the foil material of the corrugated catalyst foils to divert the flow (Fig. 2). This method provides a means for influencing the flow without reduction of the catalytic surface.

![Fig. 1: The design of the SM and LS structure.](image1)

![Fig. 2: Formation of Diversion and Separation Profiles on Corrugated Catalyst Foils](image2)

With regard to the surface coating of catalysts so structured, certain characteristics emerge. Honeycomb structures are usually coated by either the dipping or the flow-through method. To guarantee a thin coating of washcoat and to avoid blocking channels, the catalyst supports are subsequently blown through with air. However, through one of the structures shown in Figures 1 and 2, the air in the support separates into an undefined or uneven flow along the cell walls or structure through the support, which can cause accumulations of washcoat. Earlier examinations revealed an increase in washcoat accumulation in SQ structured supports in comparison...
with that of standard corrugations (Fig. 3) [5]. This increased washcoat mass exerts a negative influence on the loss of pressure and the light-off behaviour through an increase in heat capacity. Alternative procedures need to be developed to ensure even coating of these structures.

The transversal structure forces a radial component into the laminar channel flow, which improves the mass transfer and therefore catalyst effectiveness.

2.1 Flow Subject to TS Corrugation Height and Clearance

The influence exerted by transversal structure on laminar flow in the channel was studied on a flow model set up according to the law of similarity.

Experimentation with various relative TS corrugation heights and clearances determined the optimal geometric form. A compromise between influence on flow and unfavorable loss of pressure was unavoidable. The TS corrugation height for cell densities of 300 and 400 cpsi is \( \approx 0.1 \text{ mm} \) at a corrugation clearance of 4 mm.

Measurement of pressure loss in catalysts of Ø 127 x 74.5 mm, with and without transversal structure was carried out to determine the actual influence of TS corrugation on loss of pressure.

2.1.1 Influence on Loss of Pressure

On a flow test bench, under homogeneous flow conditions, pressure losses from supports with a cell density of 300 and 400 cpsi, with and without TS, were determined. Special test supports with a nominal cell density were manufactured for the test. The nominal cell density was tested at six points distributed around the cross section with the aid of an image processing facility.

The outcome was a 10% increase in loss of pressure (Fig. 5) resulting from the transversal structure. However, the 300 TS support showed an overall loss of pressure of 20% lower than the 400 cpsi supports at a mass flow rate of 600 kg/h at 20°C.

2.1.2 Influence of TS Corrugation on Heat Transfer Coefficient

The theoretical influence of TS corrugation was observed on a catalyst with a cell density of 400 cpsi. The corrugation has the same effect as dents in the channels [6]. In the vicinity of these “dents” the flow is diverted and its velocity increased. The resulting “turbulence” causes blending of the gas layer near the wall. The effect is an increase in the heat transfer coefficient and in loss of pressure. In conformance with the theory on dented tubes for the improvement of heat transfer [6], the influence of transversal structure on heat transfer is deduced by analogy.
2.1.2.1 Determination of Heat Transfer Coefficient in Channels Without Transversal Structure

Calculation of the Reynolds' number Re:

\[
Re = \frac{w \cdot dh / \theta}{107} \quad (3)
\]

Calculation of heat transfer coefficient \( \alpha \) with the aid of the Nusselt number \( \text{Nu} \) [7]:

\[
\text{Nu} = 3.97 \quad (4)
\]

\[
\Rightarrow \quad \alpha = \frac{\text{Nu} \cdot \lambda}{dh} \quad (5)
\]

\[
\alpha = 257 \text{ W/m}^2/\text{K}
\]

Calculation of the theoretical pressure loss \( \Delta p \):

The pressure loss created by a catalyst consists of channel and intake/outlet flow loss [7]. Since transversal structure exerts influence on the channel pressure loss only, intake/outlet loss of pressure has not been considered in the following.

\[
\Delta p_{\text{Channel}} = \xi \frac{1}{dh} \cdot \frac{w^2 \cdot \rho}{2} \quad (6)
\]

\[
\xi_{\text{Channel}} = 64 / Re = 0.598
\]

\[
\Delta p_{\text{Channel}} = 1044 \text{ Pa (10.44 mbar)}
\]

2.1.2.2 Determination of Heat Transfer Coefficient in Channels With Transversal Structure

According to J. Roth and W. Roetzel [6], the Nusselt number for dented tubes is

\[
\text{Nu} = B \cdot (Re^2 \cdot Pr)^m \quad (7)
\]

Applicable pressure loss coefficient \( \xi \) for channel pressure loss is

\[
\xi = E \cdot Re^q \quad (8)
\]

From research with similar dented tubes the following values can be assumed as constants for transversal structured channels [6].

\[
E = 2.344 \quad q = 0.2685
\]

\[
B = 0.1374 \quad m = 0.3786
\]

The evaluation of equations (7) and (8) establish the following:
\[ \text{Nu} = 4.24 \]
\[ \Rightarrow \alpha_{TS} = 275 \text{ W/m}^2/\text{K} \]

Determination of channel pressure loss according to equation (6):

\[ \xi_{TS} = 0.668 \]
\[ \Delta p\text{Channel }_{TS} = 1166 \text{ Pa (11.66 mbar)} \]

Theoretically, it can be seen that in TS channels under these assumptions there is an increase in loss of pressure of 12% and in the heat transfer of approximately 7% in comparison with a smooth channel. This data corresponds approximately with that of pressure losses measured (Fig. 5). The improvement in heat transfer effects a decrease in the differences between gas and structure temperatures and thus faster heating-up of the catalyst. That the mass transfer is similarly positively influenced and that the effectiveness of the catalyst can be improved accordingly, remains to be determined.

2.2 Influence of Transversal Structure on Mass Transfer

Heterogeneous gas catalysis involves the following main processes [8]:

1. Transfer of the reacting agent (CO; HC; NOx) out of the gas phase to the catalytically active outer and inner surfaces of the washcoat.
2. Adsorption of the reacting agent
3. Chemical reaction
4. Desorption of the reaction products
5. Transport of the reaction product from the inner and outer surfaces of the washcoat in the gas phase

Assuming an extremely fast reaction, the determining factor for the overall reaction velocity is the mass transfer in the channels. The following verifies that similarly to the heat transfer, the mass transfer - described by the mass transfer coefficient \( \beta \) determines the effectiveness of a certain catalytic converter volume. As a result of improved mass transport, the necessary catalytic surface can be reduced.

The required catalytic converter surface \( S \) for pollutant conversion is determined according to the following equation:

\[ S = \frac{\eta_a}{\beta} \times C_{AFM} \tag{9} \]

\[ \eta_a = \text{converted mass flow [Mol/s]} \]
\[ \beta = \text{mass transfer coefficient [m/s]} \]
\[ C_{AFM} = \text{mean concentration difference} \]

The mass flow \( \eta_a \) (Mol/s) is the result of the difference in concentration of the mass of emissions to be converted between intake and outlet of the catalyst.

Determination of the mass transfer coefficient by means of the Schmidt and Sherwood numbers.

Schmidt Number \( Sc \):

\[ Sc = \frac{\eta}{\rho D} \tag{10} \]

\( \eta \) = dyn. viscosity (Ns/m²)
\( D \) = diffusion coefficient (m²/s)
\( \rho \) = specific weight (kg/m³)

Sherwood Number \( Sh \):

\[ Sh = C \times Re^{\frac{1}{2}} \times Sc^{\frac{1}{3}} \tag{11} \]

\( C \) = non-dimensional constant

Mass transfer coefficient \( \beta \):

\[ \beta = Sh \times D/dh \text{ (m/s)} \tag{12} \]

If the intake-outlet concentrations are described with \( C_{AFE} \) and \( C_{AFA} \), the result is a mean concentration \( C_{AFM} \)

\[ C_{AFM} = \frac{C_{AFE} \times C_{AFA}}{\ln C_{AFE}/C_{AFA}} \]

In the calculation of the Sherwood number, the geometry of the catalyst channels is considered using the constant \( C \). The Sherwood number is subject to identical influences as the Nusselt number and/or the heat transfer coefficient. If the index TS identifies the factors for TS corrugation and without the index the factors for smooth channels, then

\[ C_{TS} = \frac{N_{TS}}{N_u} \times C \quad \text{and/or} \quad C_{TS} = \frac{\alpha_{TS}}{\alpha} \times C \]

also, the Sherwood number as well as the mass transfer coefficient is greater by a factor of \( \alpha_{TS}/\alpha \). The required catalytic surface area \( S \) is reduced correspondingly. Therefore, through the corrugation of the catalyst channels and the resulting increase in pressure loss, a greater heat and mass transfer coefficient occurs. The catalyst surface can be reduced but effectiveness remains unchanged.

2.3 Influence of Coating

The catalyst supports with a size of \( \varnothing 127 \times 74.5 \) mm were coated with 40 g/l, Pt/Rh 5:1. The supports were weighed before and after coating. It was established that the transversal structure does not cause increased washcoat loading.
A conclusive road endurance test with a VW Passat, 2-liter 85 kW over a distance of 160,000 km showed no impairment of any kind to the durability of TS catalysts manufactured in the proven S or SM design.

3. Comparison of TS and Production Catalytic Converters

3.1 Design

The theory established in the preceding paragraphs for improving effectiveness by increasing the mass transfer can be used to advantage in the catalytic converter layout in three ways.

Design 1: Improvement of catalytic effectiveness and light-off behaviour with constant catalyst volume and cell density.

Design 2: Reduction in pressure loss by replacing 400 cpsi catalysts by 300 TS cpsi catalysts.

Design 3: Reduction in support volume by implementing 400 cpsi TS cell density instead of 400 cpsi.

The test program described in the following will demonstrate the results of points 2 and 3. An earlier discussion of point 1 can be found in SAE paper 910837.

3.2 Theoretical Influence of Transversal Structure on Light-Off Behaviour

As a result of the increase in heat transfer (see chapter 2) created by the transversal structure, it is possible to reduce the difference between gas and structure temperatures. The effect of this, e.g in the comparison of a 400 cpsi with a 400 cpsi TS cell density, is faster catalyst heating-up time and thus improved light-off behaviour. The implementation of a 300 cpsi TS cell density, when compared with 400 cpsi standard corrugation, effects not only an advantageous pressure loss, but also a reduction in the weight of the catalyst support. The result is a reduction of the thermal mass together with a simultaneous increase in the heat transfer coefficient owing to the transversal structure, resulting in faster heating-up behaviour in the cold start phase. To establish these factors and their effect on the exhaust gas emissions, simulation calculations were carried out with the aid of a temperature and conversion program for transient data. Input data included the exhaust gas temperature in front of the catalyst, the exhaust gas mass flow and the raw emissions from a Porsche 968. The following catalyst variants were calculated:

a) 1 Catalyst, Ø 127 x 74.5, 400 cpsi
b) 1 Catalyst, Ø 127 x 74.5, 400 TS cpsi
c) 1 Catalyst, Ø 127 x 74.5, 300 TS cpsi
Figures 8 and 9 show the catalyst temperatures 10 mm behind the flow intake surface of the catalysts and the HC conversion (Fig. 8, 9).

It can be recognized that as a result of the greater heat transfer coefficient and the lower heat capacity of the 300 cpsi TS variant, catalyst temperature reaches the 300 °C mark more quickly than the 400 cpsi variant. A comparison of 400 cpsi TS and 400 cpsi converters shows as well a small advantage for TS structure even both supporting catalysts possess an identical thermal mass. The HC conversion corresponds to the rise in temperature. The calculation results show that advantages in the cold start phase can be expected from a 300 cpsi TS catalyst over a 400 cpsi catalyst. During further research, these catalysts were tested on the vehicle.

3.3 FTP Vehicle Tests

The following catalytic systems in both new and aged condition were tested on a production vehicle using FTP procedures.

Test catalytic systems:

a) 1st Monolith, Ø 127 x 74.5 mm, 400 cpsi
   2nd Monolith, Ø 127 x 74.5 mm, 400 cpsi
b) 1st Monolith, Ø 127 x 74.5 mm, 300 cpsi TS
   2nd Monolith, Ø 127 x 74.5 mm, 300 cpsi TS

3.3.1 Aging of Catalytic Converter

The aging of the catalytic converter was carried out on an engine test bench. The bench was equipped with a 5-liter engine. The exhaust gas was led to a three-way distributor. Identical conditions existed for all catalysts being tested. The reciprocal pressure loss differences of each individual catalyst system as a function of cell
density and catalyst geometry were correlated by means of values behind the catalysts. In addition to this, following each 1/3 of the testing time respectively, the converters were turned one position further in the three-way distributor.

Aging was carried out with an overall mass flow of 750 kg/h at a maximum inlet gas temperature of 930 °C at \( \lambda = 1 \). The aging time was 180 hours, whereby 5 times for 5 seconds every 5 minutes an overrun fuel cut-off was carried out (Fig. 10).

### 3.3.2 Emission results Design 2

Table 1: FTP test results

| Catalyst System | 
|-----------------|------------------|------------------|------------------|
|                 | HC (g/m³) | CO (g/m³) | NOx (g/m³) | HC (g/m³) | CO (g/m³) | NOx (g/m³) |
| a) 1. Mo Ø 127 x 74.5 | .18 | 1.8 | .04 | .41 | 4.1 | .34 |
| 2. Mo Ø 127 x 74.5; 400 cpsi | | | | | | |
| b) 1. Mo Ø 127 x 74.5 | .20 | 1.7 | .03 | .42 | 3.8 | .34 |
| 2. Mo Ø 127 x 74.5; 300 cpsi TS | | | | | | |

Vehicle test results indicate that through the implementation of the TS structure, cell density can be reduced from 400 cpsi to 300 cpsi without exerting any negative influence on the effectiveness of the catalyst. With the lower cell density, a pressure-loss advantage of 20% was possible with a simultaneous weight reduction of approximately 15%. The expected advantages in the cold start phase (Bag 1) through increased heat transfer were confirmed by the results of the emission test (Fig. 11). Bag 2 results show that no negative results arise from replacing the 400 cpsi with the 300 cpsi TS cell density. The reduction in geometric surface was compensated by improved mass transfer conditions.

### 3.3.3 Emission results Design 3

In order to study the influence of the transversal structure on 400 cpsi TS supports with reduced volume, a comparison of the following catalytic converters was carried out:

1. Monolith Ø 118 + 74.5 mm; 400 cpsi
2. Monolith Ø 118 + 150 mm; 400 cpsi
3. Monolith Ø 118 + 200 mm; 400 cpsi TS

The dynamic conversion of the aged catalytic converters was examined on an engine test bench with a VW engine (2.0-liter 85 kW) at 450 °C.

The conversion of HC, CO and NOx were determined at Lambda - 0.995 and Lambda - 1.000.

The results (Table 2) show that the transversal structure under the conditions quoted allows a reduction in catalyst volume of approximately 10% without exerting any negative influence on the dynamic conversion.

The application of these results to actual vehicle operation and the FTP cycle is at present undergoing research. Until the completion of this research, a final assessment of the potential of transversal structure for reducing catalyst volume will not be available.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Lambda = 0.995</th>
<th>Lambda = 1,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Hz +/- 1 AF</td>
<td>1 Hz +/- 1 AF</td>
</tr>
<tr>
<td></td>
<td>HC%</td>
<td>CO%</td>
</tr>
<tr>
<td>Ø 118 x 74.5; 400 cpsi</td>
<td>92</td>
<td>78</td>
</tr>
<tr>
<td>Ø 118 x 150; 400 cpsi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ø 118 x 200; 400 cpsi TS</td>
<td>91</td>
<td>79</td>
</tr>
</tbody>
</table>

Fig. 11: Individual Bag and Overall test results
4. Summary/Conclusions

The results presented here have shown that with the implementation of the Transversal Structure, new latitude has been won for the layout of metal supporting catalysts. By means of the reduction in pressure loss, weight and expenditure described, and with unchanged effectiveness, the possibility of reduced cell density and thereby geometrical catalyst surface by substituting TS corrugation for the standard technique can be used to advantage.

A research program in which a production two-piece main catalyst has been replaced with a one-piece catalyst with transversal structure at a simultaneous volume reduction of 10 % is currently in progress. Through the reduced volume and the simultaneous reduction of the number of monoliths, cost savings not only for the supporting body but also for coating and canning can be expected. This system is presently undergoing development with regard to emission stability as well as OBD II requirements.
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