The conical catalytic converter and its potential for future close-coupled converter concepts

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1 Introduction

The automobile industry has long been attempting to reduce the emissions and fuel consumption of motor vehicles in order to increase their environmental compatibility and their ability to protect resources. Thus in the last 20 years, modern technologies such as fuel injection, controlled carburetion and electronic motor management have brought about significant reductions in the level of raw emissions from engines while increasing engine performance. By employing the controlled three-way catalytic converter, it was possible as a first step to reduce vehicle emissions by 90% compared to engine raw emissions. Efforts on the part of legislators throughout the world to continually reduce permissible exhaust gas limits have forced the automobile industry and its suppliers to expend considerable sums on the development of exhaust gas treatment systems with the long-term objective of constructing vehicles with combustion engines which are at least as environmentally compatible as those of electric vehicles. In order to do this, it is necessary to attain an overall level of converter effectiveness close to the theoretical value of 100%.

To fulfill this task, it is essential that all components influencing exhaust gas quality be regarded as a system and be further optimized towards attaining the objective set.

By analyzing how the catalytic converter system functions, one can see that catalytic effectiveness is considerably influenced not only by the catalytic coating but also by the catalyst carrier, the converter casing and the geometry of the pipes leading to the converter. In this connection, it is necessary that potential for improvement be fully exploited by consideration of the following operational phases (Ill. 1), which have already been described in an earlier publication [1]:

- heat reduction phase;
- light-off phase;
- warm operational state;
- warm start phase.

This examination shows that the thermal capacity and thermodynamic properties of the catalyst carrier play a considerable role in determining the effectiveness of the converter in the individual operational phases (Phases I - IV).
In addition, various publications [2, 3, 4] have already described how the cold-start performance of a converter, i.e. the heat reduction phase (I) and the light-off phase (II), can be improved by moving the converter from the underbody to a position near the engine, a measure which is urgently required so that the next generation of permissible limit values can be attained with passive converter systems. Only when the exhaust gas flows uniformly onto the surface of the converter can the entire volume of the converter be optimally exploited so that it functions inexpensively and with a high degree of effectiveness. This assumes from the outset that the mixture control is optimal, with regard to the individual cylinders. Unevenness of flow brings about severe dynamic fluctuations of temperature and pressure in front of the converter. On one hand, this leads to increased thermal stress on the converter and thus accelerates its aging. On the other hand, fluctuations of pressure cause both the entrance cone and the converter to vibrate, thus leading to intensified mechanical stress on the components and an increased incidence of noise. Because of the cramped conditions of the engine compartment, however, a uniform flow is often very difficult to attain.

2 Flow onto the catalytic converter

For pressure loss reasons, the cross section of the catalyst carrier has to be enlarged compared to the pipe cross section. In connecting piping pieces of different diameters, it is therefore necessary to install an enlargement and/or reducer. The change in diameter at the junction can be abrupt or gradual. A gradual enlargement, i.e. a diffuser, brings about less loss of pressure than an abrupt pipe enlargement. Apart from the coarseness of the wall, geometrical
dimensions such as diameter ratio, diffuser length, and thus aperture angle have an influence on the amount of pressure lost. The form of the piping pieces in front of the diffuser also has an influence on the loss of pressure. In order to guarantee that the converter will have an optimal flow distribution with the lowest possible loss of pressure, there should be no eddying, and thus movement, of the flow away from the wall in the area of flow enlargement from the pipe to the converter cross section. The maximum permissible enlargement angle in accordance with the Reynolds' number and the coarseness of the wall is indicated as 5° - 7° [5, 6]. A cone connecting different diameters of 60 mm and 127 mm should therefore be 270 mm - 380 mm in length. Alternatively, a good distribution of flow can be attained with short, abruptly angled cones, but only at the expense of undesirably high pressure losses.

Elliptical or "racetrack"-shaped converters have typically been used to be inserted into the underbody of the vehicle. Designing an optimized inlet cone in the confined space of the vehicle was made additionally difficult due to the highly unsatisfactory relationship of the diameter of the inflow pipe to the lateral axis of the converter. Due to packaging constraints, sufficiently long cones could not be inserted into existing platforms. By using metal substrates with thinner walls and larger catalytic surfaces, it became possible to reduce the size of the converter cross section and to employ round forms more favorable to the flow distribution. These round shapes, and thus the constant and smaller ratio of the exhaust pipe and the diameter of the converter, immediately improved the flow onto the converter surface while the length of the cone remained the same. Ill. 2 compares the flow distribution of an elliptical converter with that of a round converter at the same level of catalytic effectiveness.

III. 2  Comparison of the flow distribution of a "racetrack"-shaped converter with that of a round converter

The round converter shown in Ill. 2 had an identical pressure loss because of a more uniform flow through speed despite a surface area that is 16% smaller.

As has already been demonstrated in the past [7], round substrates likewise have advantages with regard to sound projection. In the development phase of the platforms, more packaging space has been provided for new models because of the increasing importance of the converter. Therefore, cones optimized for flow could also be employed for large converters [8]. The development of diagonal inflow [9] made it possible to provide a good
quality of flow to a main converter at an angle and without additional bends. Spiral inflow, as it is known, represents a further possibility of converter inflow at an angle of 90 degrees. In this type of flow, the exhaust gas is inducted tangentially into a tapering spiral-shaped entrance funnel. In this case, the exhaust gas flows onto the converter in a way similar to diagonal flow, but with the addition of spiral flow. Ill. 3 shows the development of inlet cones and their influence on the quality of flow distribution.

III. 3 Development of inflow cones and their influence on the quality of flow distribution

Lengthy patent applications are just one example of the considerable cost of developing a uniform converter inflow. Fittings for the inlet cone such as guiding plates and flow edge projections have also been developed. Such fittings represent additional thermal mass; however, and the temperature of the gas in front of the converter is additionally lowered, thus increasing the cold start emissions. Ill. 4 shows details of drawings of different cone variants from some patent applications [10, 11, 12, 13]. Not least because of their high risk of breakdown, developments such as these could not be accepted for series production.
An alternative measure would be to employ cascade systems, as they are known, whereby the first catalyst substrate has a smaller diameter than the second, thus bringing about a more satisfactory flow distribution and better light-off performance [14].

The disadvantages of such converter systems, however, can be their relatively large overall length and somewhat more costly canning.

It has long been the wish of developers to integrate a converter into the inlet cone. By so doing, they can expect the following advantages which other solutions cannot fully provide:

- use of the cone area for the catalytic conversion of emissions;
- possible positioning closer to the engine to improve cold start performance (Phases I and II);
- improvement of converter inflow and rectification of flow and thus slower aging (Phase III).

The catalytic advantages of a cascade system [14] could thus be combined with an optimization of flow distribution. In addition, the critical sound projection of the entrance funnel caused by the pulsation of the gas would be reduced by the silencing effect of the converter matrix.

For technical reasons, it has not been feasible to produce a conical converter with the extruded ceramic carriers on the market today. One possibility is curved converters in which the flow is forced to turn through the converter channel instead of in the pipe bend. But this does not solve the actual problem of the transition from the pipe diameter to the converter diameter by means of a diffuser which is as short as possible. The manufacture of a conical honeycomb construction was made possible for the first time with the development of metallic honeycomb matrices made from individual flat and corrugated foils which are coiled and soldered into a "S" or "SM" shape, and which provide the necessary flexibility in manufacture.

3 The conical catalytic converter

3.1 Principle of construction
In order to integrate a metallic honeycomb structure into a cone, increasingly different sized cross sections (Ill. 5) have to be "filled" with one or more foils in a coiling process.

![Diagram of a cone with cross sections](image)

\[ A_{\text{small}} : A_{\text{big}} = 4:9 \]

\[ A_{\text{small}} = 28 \text{ cm}^2 \quad A_{\text{big}} = 64 \text{ cm}^2 \]

**Ill. 5 Cone cross sections**

It can be seen from Ill. 5 that in the case of a cone with a small diameter of 60 mm and a large diameter of 90 mm, the difference in cross-sectional surface area is greater than a factor of two. In order to fill the cone - assuming the same cell density on both sides - with layers of alternately flat and corrugated metal foil, more than twice as much material would be needed for the outlet side as for the inlet side in accordance with the surface ratio \( A_{\text{lg}} : A_{\text{sml}} \). To construct the conical converter in the proven or conventional "S" form, for example, would necessitate the manufacture of segments of a circle whose external arc segment \( L_2 \) is over twice as long as their internal arc segment \( L_1 \). As the height of the circle segment equals the length of the conical converter, there is only one solution to this problem. It can be seen from Ill. 6a that this solution is not very practicable from the point of view of production technology.
An alternative solution would be a lower cell density and thus a greater height of corrugation at the outlet side. As the extension factor with regard to the flat and the corrugated band remains roughly constant regardless of the cell density, the cone can be filled at both sides with the same expenditure on material when the height of corrugation is increased in accordance with the surface ratio $A_{lge.} / A_{sml}$. In practice, however, the circle segment shown in Ill. 6b with a height of corrugation ratio (HCR) of $1 / 1.5$ has proven to be effective.

**3.2 Manufacture**

The manufacture of the conical converter is divided into the following production steps and essentially corresponds to the production of an S-shaped metal catalytic converter (Ill. 7):

- cutting of the circle segments for the flat and the corrugated layers;
- corrugation of the circle segments;
- stacking of a pile made up of flat and corrugated layers;
- coiling the pile of layers into an “S” shape which is then pressed into the cone;
- high-temperature soldering process.
Cutting Corrugation Stacking

Coiling Pressing in Conical converter

Ill. 7  Steps in the production of the conical converter

The conical converter tested in the following examinations is shown in Ill. 8.

Ill. 8  The conical converter tested

4   Examination of various converter inflow concepts

Uniformity of flow onto the converter was tested in advanced underbody position with and without a conical converter and compared to diagonal inflow and spiral inflow. Overall converter volume was kept constant, but in the variant with conical converter, the main converter was reduced in size from Ø105 x 74.5 mm to Ø105 x 55 mm. The technical data of the test variants is listed in Table 1 and the variants are depicted in Ill. 9.
Table 1  
Data of the test variants

<table>
<thead>
<tr>
<th>Variant</th>
<th>converter</th>
<th>volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variant 1</td>
<td>Standard cone 23°  Ø 105 x 74.5 mm, 400 cpsi</td>
<td>0.65 l</td>
</tr>
<tr>
<td>Variant 2</td>
<td>Cone converter Ø 60 - 90 mm  Ø 105 x 55 mm, 400 cpsi</td>
<td>0.66 l</td>
</tr>
<tr>
<td>Variant 3</td>
<td>Diagonal inflow  Ø 105 x 74.5 mm, 400 cpsi</td>
<td>0.65 l</td>
</tr>
<tr>
<td>Variant 4</td>
<td>Spiral inflow  Ø 105 x 74.5 mm, 400 cpsi</td>
<td>0.65 l</td>
</tr>
</tbody>
</table>

4.1  Flow distribution and pressure loss

The angle of the curve in front of the entrance cone was 70°. The same angle was used for the variant with diagonal inflow. The examinations were made on the basis of Reynolds' numbers of 30,000 and 50,000 with regard to the entry pipe with a diameter of 50 mm. This corresponds to mass flow rates of 75 kg/h and 150 kg/h under ambient conditions.

The flow distribution measurements were made using a 10 mm grid with a hydrometric vane at a distance of 16 mm behind the main converter. Comparative examinations with a 5 mm grid and a hot-wire anemometer produced values differing only very slightly from those obtained with the coarser grid. In conjunction with the flow distribution tests, the pressure loss of the individual variants was determined. Ill. 10 shows the flow distribution values behind the main converter (corresponding to distribution in front of the converter) with a Reynolds' number of 60,000. The pressure loss is shown in Ill. 11. The flow distribution data was evaluated in accordance with the uniformity index [15]. The index represents the quality of flow as a value between 0 and 1. This can be defined as the standard deviation from mean flow speed. The value 1 represents
ideal flow distribution, so that the same flow speed prevails in each volume element of the converter. The value 0 means that the entire flow moves through one channel of the converter. The values determined in practice lie between 0.7 and 0.98.

**Ill. 10 Flow distribution and uniformity index (UI) of the individual test variants**

**Ill. 11 Pressure loss of the converter inflow concepts tested**

Compared to a standard cone diffuser with an inlet angle of 23°, the conical converter represents an improvement in uniformity of flow from 0.8 to 0.91, with the pressure loss of the standard diffuser slightly lower. It is clear from this that
the additional pressure loss of the conical converter can be offset by its better flow distribution and by the reduced size of its main converter. The diagonal flow variant produced good results similar to those of the variants with conical converter, and in comparison has the lowest pressure loss.

With regard to the spiral inflow variant (which was not, however, optimized for this application), the spiral movement means that the flow of exhaust gas lies at the outer area of the spiral because of the inertia of masses, so that converter flow through takes place primarily in the area of the converter close to the casing mantle. At 0.76, the uniformity index value is worse than that of the 23° cone. As a result of the additional losses due to friction against the wall when the flow turns around in the spiral, the spiral flow variant has the highest pressure drop. Conversely, it is also the smallest in construction.

This more uniform exploitation of the entire converter gives the user the possibility of reducing the volume of the main converter over and above the volume of the conical converter. Ill. 12 compares the inflow values of the standard 23° cone with those of the conical converter as a frequency distribution of partial space velocity according to the flow distribution measurement grid.

\[\text{Ill. 12 Frequency distribution of the partial space velocities of the 23° cone compared to the inflow with a conical converter and the catalytic conversion rate calculated according to space velocity}\]

**4.2 Calculation of converter effectiveness**

It was possible for the unsatisfactory velocity distribution, and thus the space velocity distribution, of the 23° standard cone to be evened out to an average area by means of the conical converter. The extreme values given beforehand with a 23° cone (partial space velocities of less than 120,000/h and greater than 300,000/h) were eliminated. As it is accepted that increasing space velocities mean decreasing conversion rates, it is especially worth striving to reduce high space velocity values. With the assistance of the HC conversion rate calculated
as shown in Ill. 12 and the percentage distribution of space velocity, the mean weighted conversion values of the two converter systems were calculated, and these are shown in Ill. 13.

The calculated mean weighted conversion rate can be increased from 90.3% to 91.4% by means of the better flow distribution with the conical converter. This produces a volume reduction factor of approx. 10% by which the overall converter volume can be reduced and at the same level of effectiveness.

5 Synopsis

The development of the highly durable S-shaped metal substrates has provided the blueprint for conical converters with a similar honeycomb structure that have continually broadening channels for manufacturing. The conical converter represents a new possibility of improving the flow distribution for a converter system. Flow examinations demonstrated existing potential for improvement and produced the following results:

- Flow distribution with a conical converter shows a clear improvement compared to the standard cone with $23^\circ$ aperture angle and to spiral inflow. Diagonal inflow produced similar results.
- Because of the improved flow distribution, it was possible to improve the ratio of maximum to minimum space velocity by over 50%.
- The additional pressure loss of the conical converter can be offset by the better quality of the inflow and because of a reduction in size of the main converter by at least the volume of the conical converter.
- By making use of the entrance cone as converter volume, construction volume can be reduced in comparison to diagonal inflow, for example.
- Due to the better flow distribution of the diagonal inflow and the variant
with conical converter, converter volume can be reduced by approx. 10%.

This reduction of overall converter volume offers the potential to compensate at least in part for the additional costs of a system with conical converter.

Many theoretical advantages of the conical converter remain to be investigated. These include

- improvement of cold-start characteristics (Phases I and II) and the effectiveness of the converter both when new and in an aged state;

- evening out of flow distribution with regard to the influence of individual cylinders with manifolds optimized for torque and the converter positioned close to the engine;

- reduction in premature localized aging.

Extensive tests still need to be performed on engine test stands and in the vehicle in order to prove long-term mechanical stability and catalytic effectiveness.